Coastal and Hydraulics Laboratory

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US Army Corps of Engineers®
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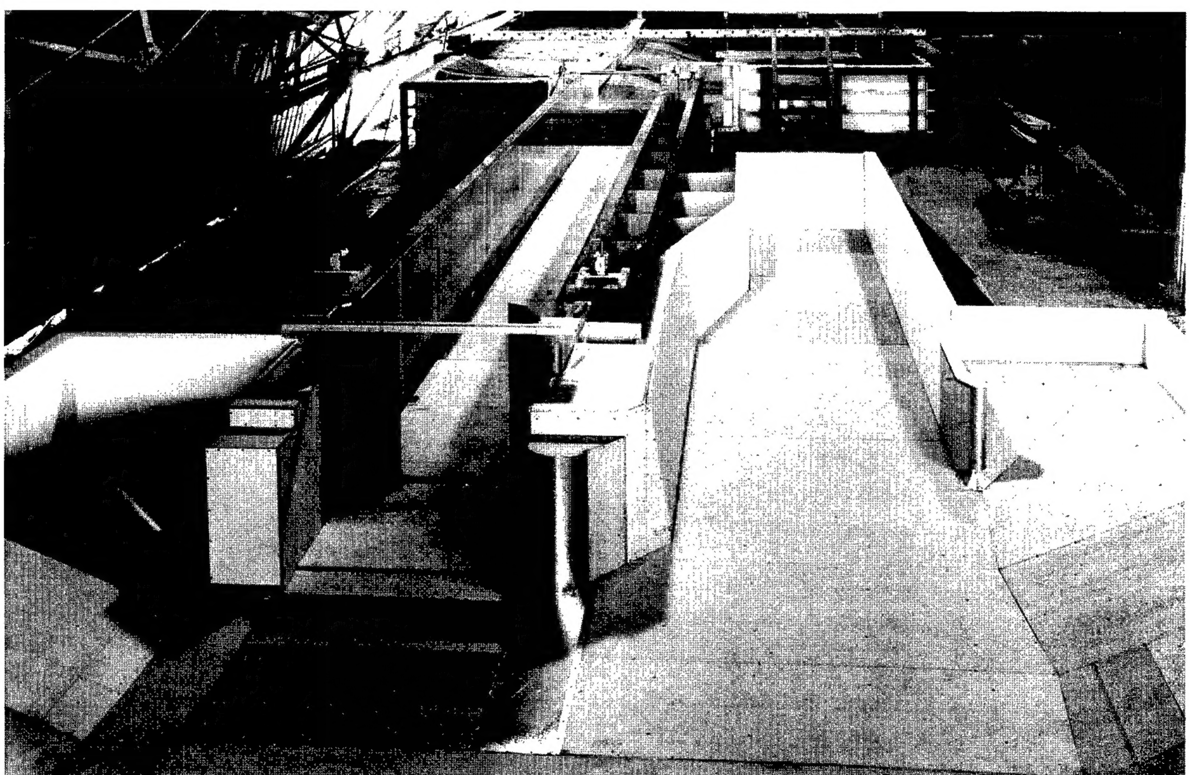
Model Study of Kentucky Lock Addition, Tennessee River, Kentucky

Hydraulic Model Investigation

Jose E. Sanchez

May 2001



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Model Study of Kentucky Lock Addition, Tennessee River, Kentucky

Hydraulic Model Investigation

by Jose E. Sanchez

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Final report

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Prepared for U.S. Army Engineer District, Nashville
Nashville, TN 37203-3863

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Preface

The model investigation reported herein was performed for the U.S. Army Engineer District, Nashville. The study was authorized by the Nashville District on 1 July 1995, and Mr. Don Getty, Nashville District, directed the study.

The work was conducted in the Coastal and Hydraulics Laboratory (CHL) of the U. S. Army Engineer Research and Development Center (ERDC) during the period of July 1995 to March 2000 under the direction of Dr. James R. Houston, former Director, CHL; Mr. Charles Calhoun, Jr., former Assistant Director, CHL; and Dr. Phil G. Combs, Chief, Rivers and Structures Division, CHL.

The experimental program was led by Mr. Jose E. Sanchez and Mr. James Crutchfield, Locks and Conduits Group, CHL. Dr. John Hite, Leader, Locks and Conduits Group, CHL, and Mr. Charles Tate, Fisheries Branch, CHL, were consulted throughout the investigation for assistance in data analysis and results. Model construction was performed by Messrs. J. A. Lyons, K. Rainer, J. Jeffers, and C. H. Hopkins, Model Shop, Department of Public Works, ERDC, under the supervision of Mr. J. Schultz, Chief, Model Shop. Data acquisition and remote-control equipment were installed and maintained by Messrs. S. W. Guy, J. Ables (retired), L. Koestler, and T. Nisley, Information Technology Laboratory (ITL), ERDC. Data acquisition software was developed by Dr. B. W. McCleave, ITL. The report was written by Mr. Jose E. Sanchez.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and Mr. Armando J. Roberto, Jr., was Acting Commander.

1 Introduction

Background

Many projects operated by the U.S. Army Corps of Engineers are facing the challenge of increasing the lockage capacity at their projects to accommodate increases in tow traffic. In the Nashville District, this problem was encountered at Kentucky Lock & Dam. The existing Kentucky Lock is operating at capacity. Products from 20 States pass through Kentucky and Barkley locks, the lowermost locks on the Tennessee and Cumberland rivers, respectively. Traffic levels are expected to increase in the future, and an additional navigation lock is needed to satisfy the increased capacity requirements. A feasibility report completed in 1992 recommended adding a new 33.53-m × 365.76-m (110' × 1,200') lock adjacent and landward of the existing 33.53-m × 182.88-m (110' × 600') lock. The project was authorized for construction in Water Resources Development Act (WRDA) 96.

Prototype

The existing Kentucky Lock and Dam is located in western Kentucky at river mile 22.4 of the Tennessee River approximately 32.18 km (20 miles) southeast of Paducah, KY (Figure 1). The project consists of a gated spillway to regulate river flows, a powerhouse for hydroelectric power generation, and a 182.88-m- (600-ft-) long navigation lock for moving industrial tow traffic and recreational boats through the project. Description of lock features and nomenclature used in this report can be found in Engineer Manual 1110-2-1611 "Layout and Design of Shallow-Draft Waterways," EM 1110-2-2602 "Planning and Design of Navigation Locks," and EM 1110-2-1604 "Hydraulic Design of Navigation Locks." The new 1,200-ft lock will be located landward of the existing lock with the upstream pintles (cross-stream axis of the miter gates) located just over 30.48 m (100 ft) downstream from the upstream pintles of the existing lock.

The normal upper pool elevation for the Kentucky Lock project is 357.0 and the normal lower pool elevation[1] is 304.2 resulting in a lift of 16.093 m (52.8 ft), which is characterized as a medium-lift lock.

[1] All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD) (To convert feet to meters, multiply by 0.3048).

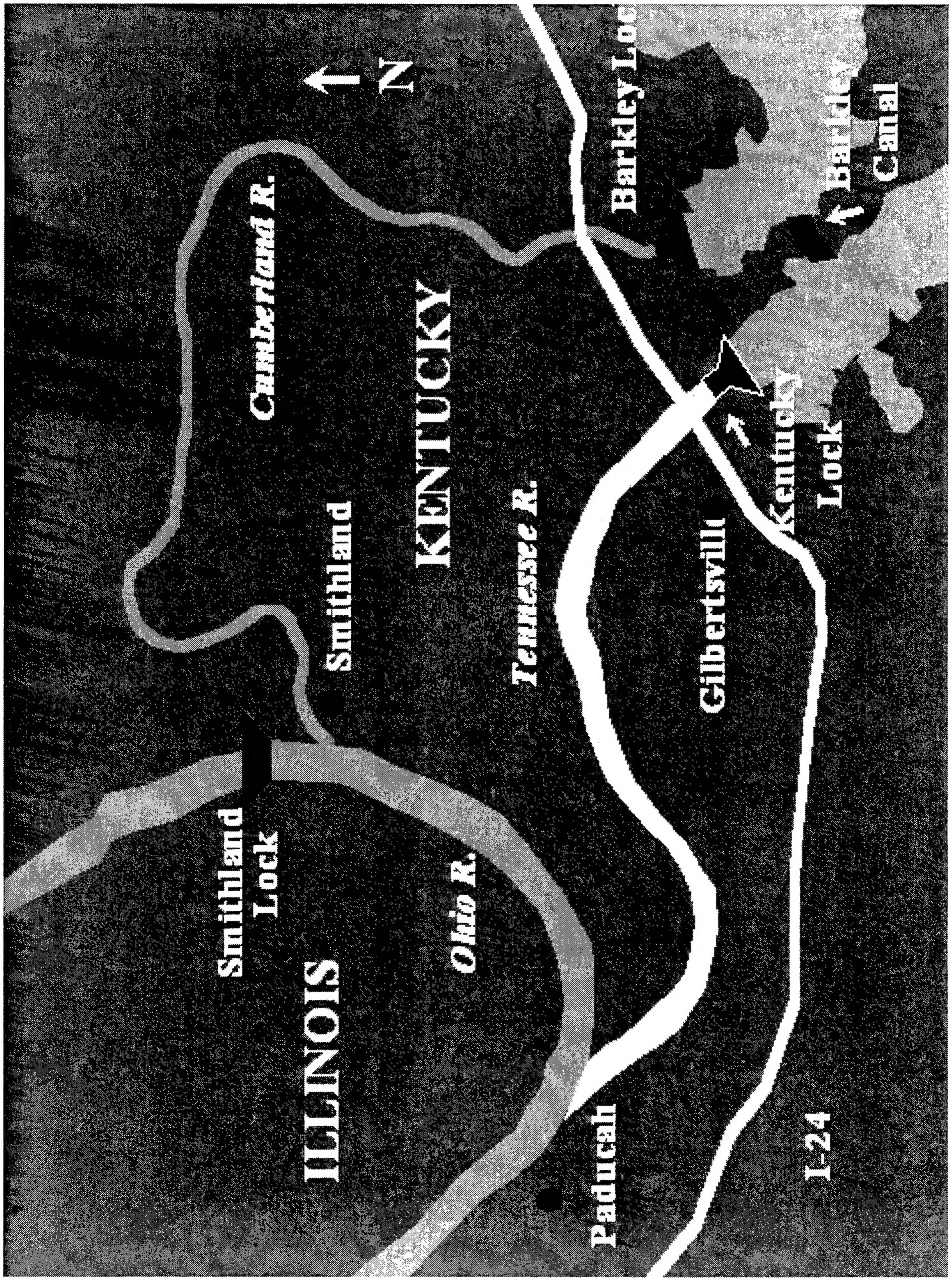

Figure 1. Vicinity map

The new lock discussed in this report features a through-the-sill intake that carries flow to a multiport filling and emptying system, and an interlaced lateral discharge system located 33.53 m (110 ft) downstream of the lower miter gates.

Purpose and Scope

The purpose of this model study was to evaluate the hydraulic performance and modify the filling and emptying system, if necessary, to provide a design acceptable to the Nashville District and the Towing Industry for the Kentucky Lock Addition.

Specifically, the study was to determine the following:

a. Performance of the through-the-sill intakes.

b. Filling and emptying times for various valve speeds at the design lift of 16.093 m (52.8 ft).

c. Flow conditions in the lock chamber during filling and emptying operations.

d. Hawser forces exerted on barges moored in the lock chamber for various valve speeds at the different lifts.

e. Performance of the interlaced lateral discharge system.

f. Pressures in the culvert.

g. Longitudinal hawser forces exerted on barges moored in the lower lock approach during emptying operations.

h. Longitudinal hawser forces exerted on barges moored in the upper lock approach during filling operations.

2 Physical Model

Description

The 1:25 scale model reproduced approximately 457.2 m (1,500 ft) of the upstream approach including the proposed floating guide wall, the existing lock approach and its corresponding floating guide wall, and the respective guard walls for both locks. The intakes, miter gates, entire filling and emptying system including culverts and valves, interlaced lateral discharge outlet, and approximately 396.24 m (1,300 ft) of the topography in the downstream approach were also reproduced. The intake, outlet, lock walls, and filling and emptying system were constructed of acrylic plastic. The upper and lower approaches were constructed of plastic-coated plywood and concrete.

Details of the lock design are shown in Plates 1 and 2. The filling and emptying system begins upstream with a multiported intake located in the upstream face of the miter gate sill. Each port is 7.1 m (23.3 ft) wide by 7.1 m (23.3 ft) high at the face of the intake. Figure 2 shows the model intake looking downstream. Each half of the intake transitions to 4.57-m- (15-ft-) wide by 4.57-m- (15-ft-) high culverts located in the lock walls where the filling valves and bulkheads are located. Figure 3 shows the filling valve well and downstream culvert. Downstream from the filling valve, the inside culvert wall converts into the multiport filling system. The 398 ports located in the culvert walls have an outside diameter of 38.1 cm (15 in) and reduce to 25.4 cm (10 in) in the center. The ports are placed in two rows on each culvert and extend from sta 3+59.33 to sta 10+90.33. Plate 2 shows the port details. Downstream from the ports, the culverts continue to the emptying valves and bulkheads. Figure 4 shows a view of the lock chamber looking downstream. The filling and emptying system ends downstream with an interlaced lateral discharge outlet located 33.53 m (110 ft) downstream of the lower miter gates. Plate 3 shows the discharge outlet details. The outlet is also visible in Figure 5, which shows a view of the model looking upstream.

Appurtenances and Instrumentation

Water was supplied to the model through a circulating system. Constant head weir systems located in the head bay and tail bay maintained the upper and lower pools during filling and emptying operations. Vertical adjustments of the

Figure 2. Dry bed view of model intakes looking downstream

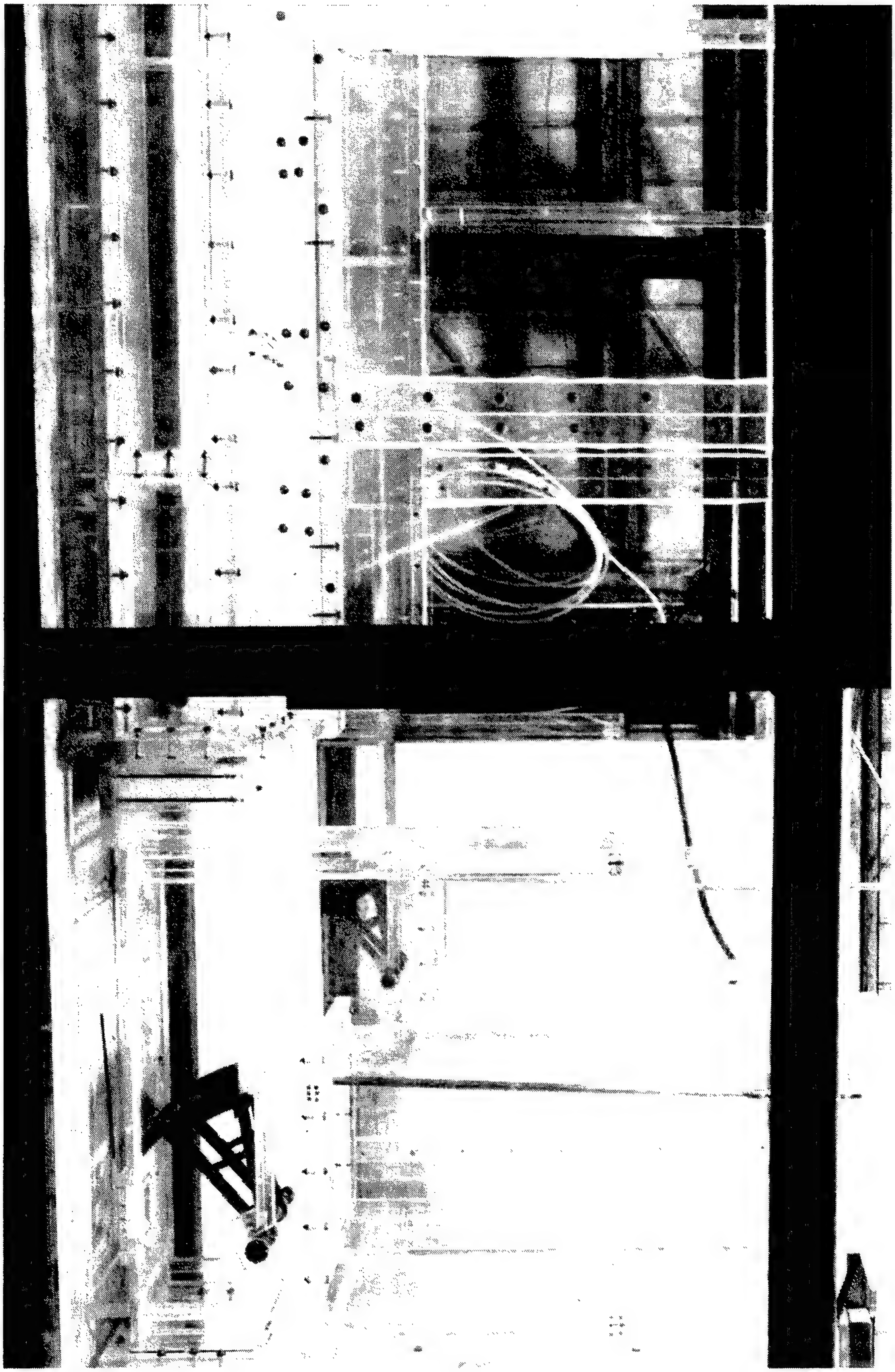

Figure 3. Side view of riverside filling valve well and culvert

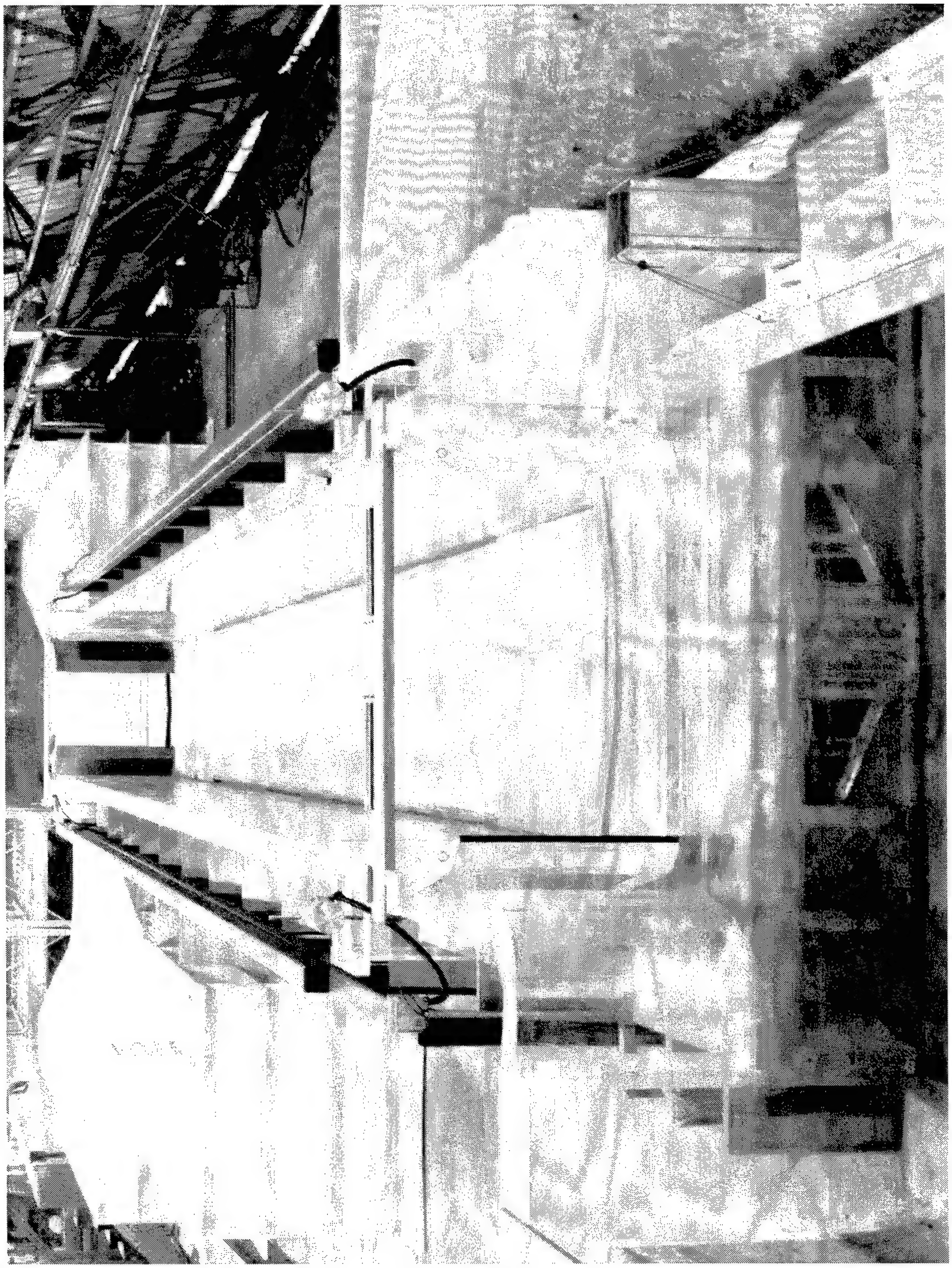

Figure 4. View of lock chamber looking downstream

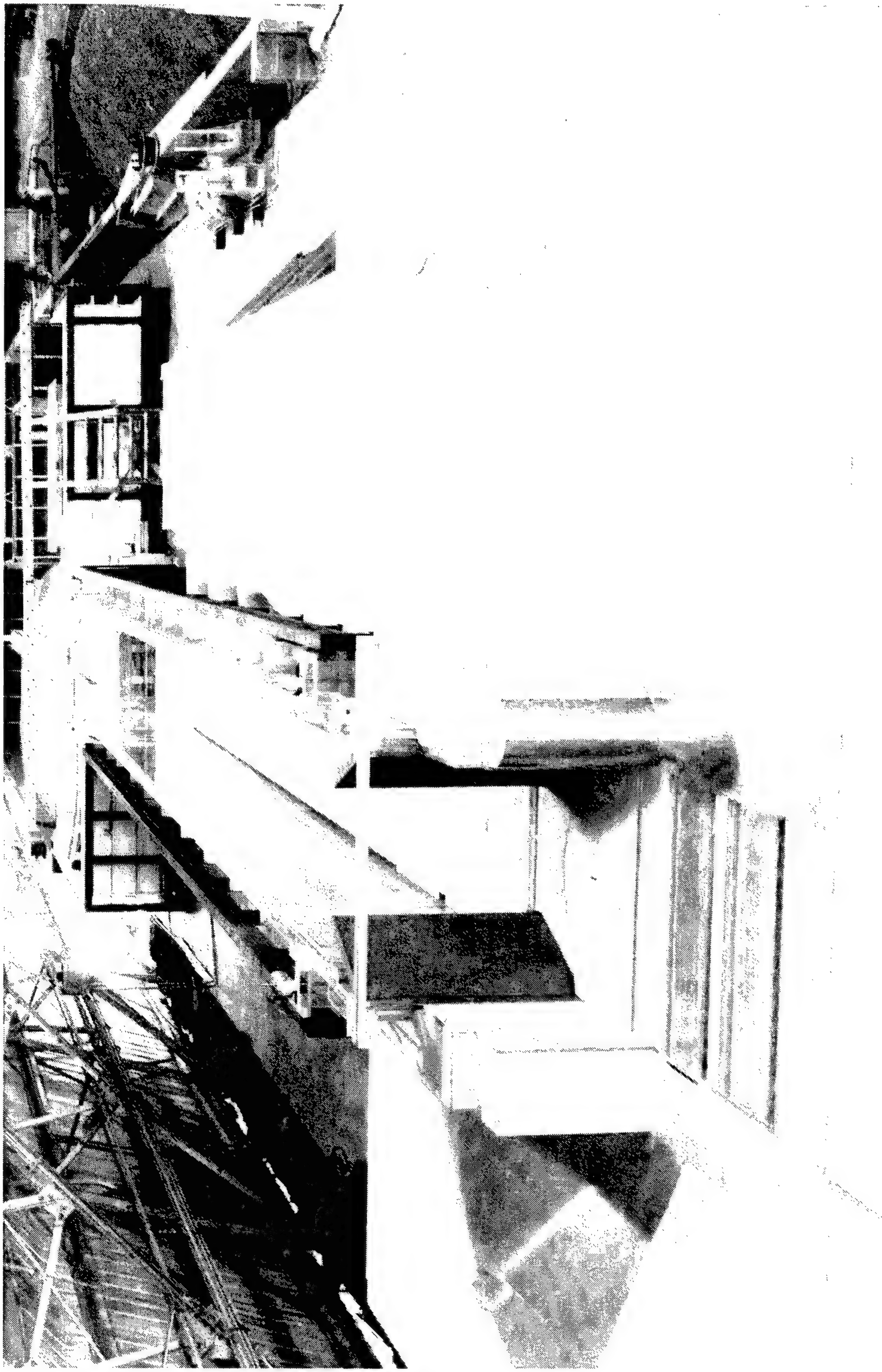

Figure 5. View of lock chamber and emptying system looking upstream

skimming weirs permitted simulation of any desired upper and lower pool elevations. Dye and confetti were used to study subsurface and surface current directions. Pressure cells were used to measure instantaneous pressures in the culvert just downstream of the filling valve and to record water-surface elevations in the lock chamber and the lower lock approach. The pressure cells located within the chamber measured the water-surface variations in time at the upstream end, center and downstream end. Histories of the end-to-end water-surface differential were also recorded during operations. The pressure cells located in the lower lock approach measured the water-surface variations in time between sta 16+98 and sta 22+97 during the emptying cycle.

The movement of the culvert valves was controlled by servo-driven linear actuators that were regulated by the output from a personal computer. Programming of the personal computer resulted in varied output allowing the desired valve schedule to be reproduced. An automated data acquisition and control program, "Lock Control," which was written by Dr. Barry Mc Cleave of the Engineer Research and Development Center (ERDC), Information Technology Laboratory (ITL) was used to control the valve operations and collect pressure and strain gage data.

Eleven data channels were used, four for control of the filling and emptying valves, four for pressure data, and three for collecting strain gage information. The data were usually collected at a sampling rate of 50 Hz. Some of the hawser force and lock filling and emptying data were collected at 10 Hz. These data were then processed using spreadsheet software. The processed data were used to determine lock filling and emptying times, longitudinal and transverse hawser forces, and pressures downstream from the filling and emptying valves.

A hawser-pull (force links) device used for measuring the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying operations is shown in Figure 6. Three such devices were used: one measured longitudinal forces and the other two measured transverse forces on the downstream and upstream ends of the tow, respectively. These links were machined from aluminum and had SR-4 strain gages cemented to the inner and outer edges. When the device was mounted on the tow, one end of the link was pin-connected to the tow while the other end was engaged to a fixed vertical rod. While connected to the tow, the link was free to move up and down with changes in the water surface in the lock. Any horizontal motion of the tow caused the links to deform and vary the signal, which was recorded with a personal computer using an analog-to-digital converter. The links were calibrated by inducing deflection with known weights. Instantaneous pressure and strain gage data were recorded digitally with a personal computer.

Similitude Considerations

Kinematic similitude

Kinematic similarity is an appropriate method of modeling free-surface flows in which the viscous stresses are negligible. Kinematic similitude requires that

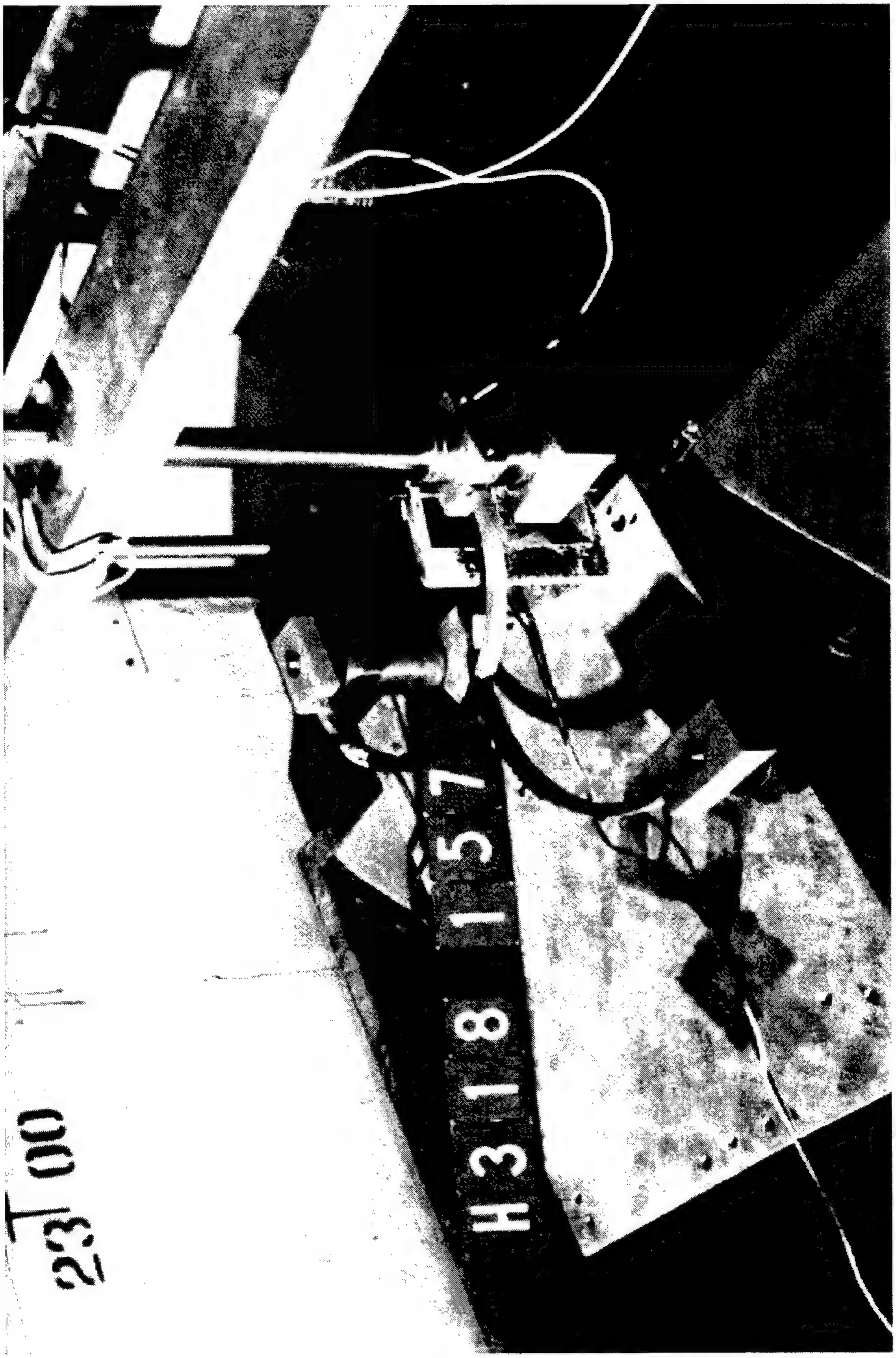

Figure 6. Hawser-pull (force links) measuring device

the ratio of inertial forces ($\rho V^2 L^2$) to gravitational forces ($\rho g L^3$) in the model are equal to those of the prototype. Here, ρ is the fluid density, V is the fluid velocity, L is a characteristic length, and g is the acceleration due to gravity. This ratio is generally expressed as the Froude number, N_F.

$$N_F = \frac{V}{\sqrt{gL}} \tag{1}$$

where L, the characteristic length, is usually taken as the flow depth in open-channel flow.

The Froude number can be viewed in terms of the flow characteristics. Because a surface disturbance travels at celerity of a gravity wave, $(gh)^{1/2}$, where h is the flow depth, it is seen that the Froude number describes the ratio of advection speed to the gravity wave celerity. Evaluation of the lock chamber performance primarily concerns modeling of hawser forces on moored barges during filling and emptying operations. These hawser forces are generated primarily by slopes in the lock chamber water surface. The tow's bow-to-stern water-surface differentials are the result of long period seiches or oscillations in the lock chamber. Seiching is gravity waves traveling in the longitudinal direction from the upper miter gates to the lower miter gates. Equating Froude numbers in the model and prototype is an appropriate means of modeling the lock chamber.

Dynamic similitude

Modeling of forces is a significant purpose of the laboratory investigation. Appropriate scaling of viscous forces requires the model be dynamically similar to the prototype. Dynamic similarity is accomplished when the ratios of the inertia forces to viscous forces (μVL) of the model and prototype are equal. Here, μ is the fluid viscosity. This ratio of inertia to viscous forces is usually expressed as the Reynolds number (N_R):

$$N_R = \frac{VL}{\nu} \tag{2}$$

where ν is the kinematic viscosity of the fluid ($\nu = \mu/\rho$) and the pipe diameter is usually chosen as the characteristic length, L, in pressure flow analysis.

Similitude for lock models

Numerous studies conducted to investigate vortex formation at intakes associated with critical submergence (generally defined as the submergence where an air-core vortex enters the intake) have indicated that the Froude number is an important parameter. The Froude number similarity is customarily used to model vortices although corrections to model results are sometimes used to account for surface tension and viscous effects between the model and the

prototype (Knauss 1987). Using a scale of 1 to 25 (model to prototype), as is the case with this lock model, minimizes the surface tension and viscous effects and provides acceptable results based on the Froude number similarity.

Complete similitude in a laboratory model is attained when geometric, kinematic, and dynamic similitudes are satisfied. Physical models of hydraulic structures with both internal flow (pressure flow) and external flow (free surface) typically are scaled using kinematic (Froudian) similitude at a large enough scale so that the viscous effects in the scaled model can be neglected. More than 50 model and 10 prototype studies of lock filling and emptying systems have been investigated (Pickett and Neilson 1988). The majority of these physical model studies used a scale of 1 to 25 (model to prototype). Lock model velocities scaled using kinematic similitude (model Froude number equal to prototype Froude number) in a 1:25-scale model have maximum Reynolds numbers at peak discharges on the order of 10^5 yet the corresponding prototype values are on the order of 10^7.

Boundary friction losses in lock culverts are empirically described using the "smooth- pipe" curve of the Darcy-Weisbach friction factor where the head loss is expressed as

$$H_f = f \frac{L}{D} \frac{V^2}{2g} \tag{3}$$

where

H_f = head loss due to boundary friction

f = Darcy-Weisbach friction factor

L = culvert length

D = culvert diameter

The Darcy-Weisbach friction factor for turbulent flow in smooth pipes is given in an implicit form as (Vennard and Street 1982)

$$\frac{1}{\sqrt{f}} = 2.0 \log\left(N_R \sqrt{f} \right) - 0.8 \tag{4}$$

Because f decreases with increasing N_R, the model is hydraulically "too rough." The scaled friction losses in the model will be larger than those experienced by the prototype structure. Consequently, the scaled velocities (and discharges) in the model will be less and the scaled pressures within the culverts will be higher than those of the prototype. Low pressures were not a major concern with the Kentucky Lock design; however, the lower discharges would in turn result in longer filling and emptying times in the model than the prototype will experience. Prototype filling and emptying times for similar designs will be less than those measured in a 1:25-scale lock model.

Modeling of lock filling and emptying systems is not entirely quantitative. The system is composed of pressure flow conduits and open-channel components. Further complicating matters, the flow is unsteady. Discharges (therefore N_F and N_R) vary from no flow at the beginning of an operation to peak flows within a few minutes and then return to no flow at the end of the cycle. Based on many years of experience (over 50) in conducting large-scale models, and subsequently, studying the corresponding prototype performance, a 1:25-scale Froudian model was used in which the viscous differences were small and could be estimated based on previously reported model-to-prototype comparisons. Setting the model and prototype Froude numbers equal results in the following relations between the dimensions and hydraulic quantities:

Characteristic	Dimension[1]	Scale Relation Model:Prototype
Length	$L_r = L$	1:25
Pressure	$P_r = L_r$	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3, 125
Time	$T_r = L_r^{1/2}$	1:5
Force	$F_r = L_r^3$	1:15,625

[1]Dimensions are in terms of length.

These relations were used to transfer model data to prototype equivalents and vice versa.

Experimental Procedures

Evaluation of the various elements of the lock system was based on data obtained during typical filling and emptying operations. Performance was based primarily on roughness of the water surface, hawser forces on tows in lockage, pressures, and time required for filling and emptying.

3 Model Experiments and Results

Intake Vortex Experiments

The initial model experiments were performed to determine the lock approach flow conditions and the performance of the intake. Intakes placed in the miter gate sill are more prone to vortex formation than intakes located upstream and outside the lock approach walls (Hite 1999). The performance of the intakes was based on the observation of approach flows and classification of the maximum strength vortex that formed in the lock approach during the filling cycle. The Alden Research Laboratory Vortex Classification (Padmanabhan and Hecker 1984) shown in Plate 4 was used to document the strength of observed vortices. The strength of a vortex may range from a type 1 which is a noticeable surface swirl to a type 6, which is a full air-core to the intake. Vortices stronger than a type 3 are not desirable in a Froude model of this scale. The type 3 vortex has a visual dye core from the water surface to the intake, which could be observed if one were able to inject dye into a vortex of this strength. Dye was not injected into the vortex during these model experiments since the injection process may affect the strength of the vortex. Type 2 and type 4 vortices are fairly well defined, and any vortex with a strength in between is classified as a type 3 vortex.

Generally, model experiments were repeated as time allowed to fully evaluate vortex formation. A 20-min stilling period was allowed before each filling cycle was initiated or repeated to let false or residual currents dissipate in the flume; however, model results were not always repeatable even with this experimental procedure. It is not uncommon in unsteady flow experiments documenting vortex strengths to observe different results since initial conditions will not always be exactly the same. A minimum of five filling cycles were used to determine the performance of each headwater and tailwater combination, and respective valve speeds, but additional experiments were often conducted to further evaluate or verify the performance of a specific condition.

Type 1 approach design

Several pool levels for headwater and tailwater were used. Upstream levels ranged from el 375 to el 346, while the downstream levels were between el 322.8 and el 300. The pool levels desired by the Nashville District were evaluated during the first set of experiments. The type 1 approach design included an existing fishing pier, a separation between the center line of the existing lock and the proposed lock of 60.96 m (200 ft), a floating guide wall with a 3.66-m (12-ft) pylon, and the minimum excavation scheme. The flow pattern with this design showed a counterclockwise circulation (viewed from above) in front of the intakes. Any vortex that formed during the filling cycle was drawn into the miter gate sill where the intakes were located. The vortex would usually pass over the intakes and into the area just upstream from the miter gates where it would dissipate.

During filling operations, the flow approached the intake from the following two directions: a) part of the flow passed underneath the floating guide wall into the landside; and b) the remaining flow generally approached the intakes in the streamwise direction. The flow that passed under the floating guide wall continued to move downstream between the floating guide wall and the bank and then approached the intakes by moving underneath the wall again. The shear zone created by the two approaching flows often initiated vortex activity. The results from vortex experiments conducted for selected pool levels and filling operations are presented in Tables 1 to 16. Lower headwaters (HW) and fast filling valves created stronger vortices. The strongest vortices were seen with a HW el 354, a tailwater (TW) el 301.5, and a 1.0-min valve time. A type 5 vortex was the maximum observed (Table 11, Experiment 1). Type 4 vortices were observed with two conditions (Tables 11 and 15).

Type 2 approach design

A meeting between the ERDC Coastal and Hydraulics Laboratory (CHL) and the Nashville District was held on August 26, 1996 to observe the model and discuss the model results. At this meeting, it was decided that the separation between the center lines of the locks should be increased to 65.53 m (215 ft) and that the fishing pier should be eliminated from the topography. It was also noted that the most critical flow condition occurred with a HW el of 354, a TW el of 301.5, and a 1.0-min valve. The modification to the upstream topography changed the approach flow pattern. The circulation in front of the intakes changed to a clockwise rotation. The vortices that formed moved upstream close to the floating guide wall and the duration of the vortices was longer and stronger since the vortex appeared stabilized. Tables 17 and 18 provide the results for experiments performed with the most severe flow conditions identified from previous experiments and the type 2 approach design. A type 5 vortex was the maximum observed for both valve times.

Type 1 solid curtain design. Solid curtains were placed in the model to evaluate the effect on vortex formation. A solid curtain was placed on the landside of the floating guide wall to prevent the flow from interacting with the

streamwise flow approaching the intake. A HW of 354 and a TW of 301.5 with only the 1.0-min valve was used for evaluation, since this condition created the strongest vortices. Different curtain configurations were used. The first design consisted of a 24.08-m- (79-ft-) long curtain with varying submergence (type 1 curtain design) placed in the connection of the floating guide wall and the face of the intake. The submergence of the curtain was increased at 3.048-m (10-ft) intervals. The submergence was determined by measuring the distance from the water surface to the bottom edge of the curtain. Table 19 lists the results for the different submergence conditions of the curtain. Results indicated the greater the submergence, the weaker the vortices. The decrease in vortex strength was not considerable, but reduction in strength from a type 4 to a type 3 vortex was observed. Four experiments were conducted with a 10.973-m (36-ft) curtain submergence because results showed a potential strength reduction in vortex formation. The strongest vortex observed with the 10.973-m (36-ft) submergence was a type 4 vortex in the first experiment.

Type 2 solid curtain design. The type 2 curtain design measured 48.158 (158 ft) in length and was submerged 10.973 m (36 ft). Table 20 lists the results for five experiments with a HW el 354, a TW el 301.5, and a 1.0-min valve. A type 4 vortex was the maximum strength vortex observed. The duration of the circular pattern in front of the intake was increased and the vortex location was stabilized. The vortex stabilization suggested that the curtain design was not appropriate and that further modifications were needed.

Type 3 approach design

Experiments were conducted with modifications that reproduced placing the fishing pier back in the model and closing off the open flow area between the end of the fishing pier and the floating guide wall (type 3 approach design). Closing off the flow area blocked the flow approaching from the landside of the floating guide wall and reduced the amount of flow going underneath the floating wall. The results from these experiments are provided in Table 21. A type 2 vortex was the maximum strength observed in these experiments. These results, indicated the type 3 approach design, was effective in reducing vortex activity.

Type 4 approach design

The navigation industry had concerns with the original design of the upstream guard wall. Another design was developed by the Nashville District to address these concerns. The new guard wall shown in Plate 5 (type 4 approach design) was a floating guard wall that slid in grooves attached to the riverside upstream lock approach wall and in the impact protection nose. The type 4 approach design included the existing fishing pier, but the area between the end of the pier and the floating guide wall was not closed off. The guard wall had a draft of 2.896 m (9.5 ft) and was capable of floating at all the HW elevations tested. The impact protection nose was mounted in three caissons anchored to the riverbed. The location of the caissons presented a concern for possible vortex formation, and a second set of experiments was conducted to address this issue.

The pools used during these experiments were selected from previous experiments as being more prone to vortex activity. The upstream pools studied were el 354 and el 359, and el 301.5 for the downstream pool. The results are presented in Tables 22-25. A type 4 vortex was the maximum strength observed during these experiments, and only in one experiment.

The vortex activity was concentrated in front of the left intake (looking downstream) approximately 18.288 m (60 ft) upstream of the face of the miter sill and less than 3.048 m (10 ft) from the floating guard wall (Figure 7). The vortices appeared in this area frequently and had a short duration. The strength often reduced in a matter of seconds in the model. Halfway into the filling cycle, flow patterns in this area portrayed characteristics of an unstable condition. The flow around the corner from the existing lock pier and through the nose caissons interacted with the flow in the lock approach area that had a streamwise direction. This flow interaction caused strong circulation in this area. Figure 8 shows a dye and confetti time-lapse photography of the flow conditions previously mentioned.

The floating guard wall was removed from the model and some of the experiments were repeated to observe flow patterns without the floating wall. A type 6 vortex formed in the area the guard wall was located. This indicated that the flow patterns created by the interaction of the riverflow with the caissons, the existing lock pier and the minimum excavation scheme in the lock approach, were prone to strong vortices. The floating guard wall was dissipating some of this activity. After discussing the findings with the Nashville District, it was recommended that the topography in the upstream lock approach needed additional modifications.

Type 5 approach design

The topography in the upstream lock approach was modified to include a smooth transition into the intakes. Plate 6 shows the changes made to the topography. Experiments were conducted to compare the results with the previous findings. Tables 26-29 list the results obtained with various HW and TW combinations. A type 2 vortex was the maximum observed in these experiments. The flow patterns in the lock approach were improved and flow instabilities in the area were not noticed.

Hawser Force Measurements

Experiments were conducted to measure hawser forces for a three by six-barge arrangement secured inside the lock chamber. Several upper pool and lower pool combinations were tested. They ranged from el 354 to el 359 upstream and el 301.5 and el 304.2 downstream. A typical experiment had an upper pool of el 357 and lower pool of el 304.2. This lift of 16.093 m (52.8 ft) was selected because it represented the 50 percent duration in the proposed lock operations. From hereafter, when the 16.093-m (52.8-ft) lift is mentioned in this report the upper pool el is 357 and lower pool el is 304.2, unless otherwise

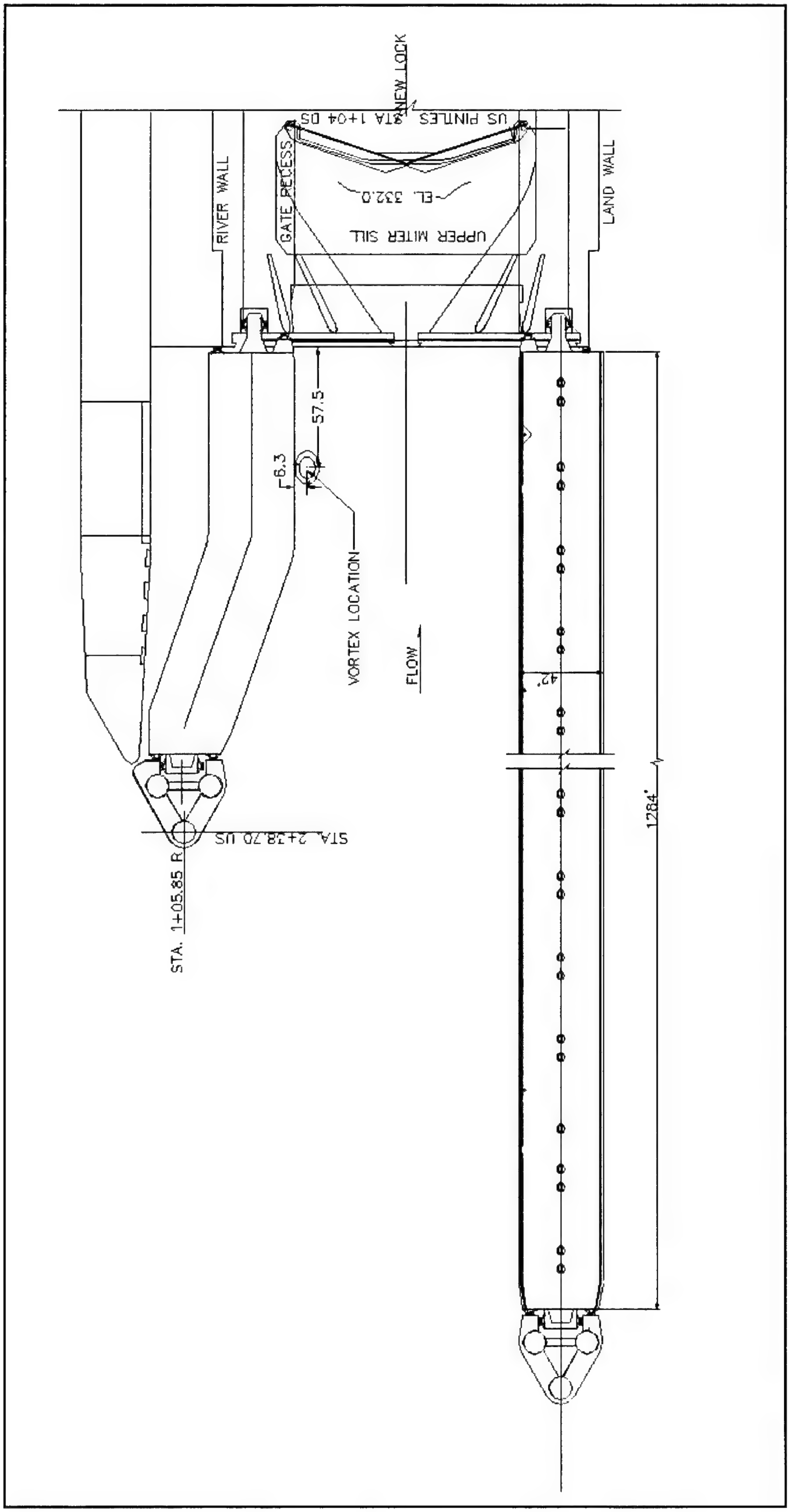

Figure 7. Vortex location with type 4 upstream approach design

Figure 8. Vortex experiment with type 4 approach design

specified. As discussed previously, a hawser pull (force links) device was used for measuring the longitudinal and transverse forces on a tow in the lock chamber during the filling and emptying operations (Figure 6). Hawser force measurements were conducted with a 1.5-, 3.0-, 7.0-, and 11.72-min valve operations. Plate 7 shows the maximum hawser force results for the 16.093-m (52.8-ft) lift. The valve schedule utilized for the experiments is shown in Plate 8.

Filling operations

Longitudinal hawser forces, 1.5-min valve. Results from a typical experiment with the 1.5-min valve operation and a 16.093-m (52.8-ft) lift are shown in Plate 9. Time-histories of the upstream and downstream longitudinal and side to side transverse hawser forces are shown. The lock water-surface elevation is also shown and was determined by averaging the piezometric head from pressure cells mounted in the middle and on both ends of the lock. The longitudinal hawsers indicate that immediately after the valve begins to open, the barges inside the lock experience a negligible upstream-directed hawser force for a few seconds and then begin to experience a significant downstream-directed hawser force that is sometimes the maximum force experienced during the filling operation. Between 1 and 3 min into the filling cycle, the longitudinal hawser force direction changes from downstream to upstream, and the maximum upstream hawser force was experienced 2.0 min into the filling operation. These first two hawser force peaks had similar magnitudes. The longitudinal hawser force then begins to fluctuate between the downstream and upstream directions, and the magnitude is reduced with time. The original design included a "man port" located on both sides of the downstream end of the lock chamber past the last set of multiports. The man port was designed to facilitate access of maintenance personnel into the culverts (Plate 18).

As mentioned previously, maximum hawser forces measured with the original design (man port open) filling and emptying system with an upper pool el 357 and a lower pool el 304.2 for 1.5-, 3.0-, 7.0-, and 11.72-min valves are shown in Plate 7. The filling times and maximum hawser forces shown are an average value computed from several experiments. Experiments were repeated to ensure consistency. The average of the maximum longitudinal hawser forces measured with the 1.5-min valve was 189494.24 N (21.3 tons) in the upstream direction and 193052.818 N (21.7 tons) in the downstream direction. These longitudinal hawser forces were considerably higher than the 5.0-ton limit suggested by the Corps' design guidance (EM 1110-2-1604).

Transverse hawser forces, 1.5 min. valve. Transverse hawser forces measured for a typical experiment with a 1.5-min valve operation are shown in Plate 9. The transverse hawser forces regularly fluctuate from right to left (looking downstream) with the largest magnitudes occurring between 1.5 and 2.5 min into the filling cycle. These magnitudes were always less than the longitudinal hawser forces. The average maximum transverse hawser force observed in the upstream end of the lock with a 1.5-min valve was 48930.438 N (5.5 tons) on the right side (looking downstream), and 56047.592 N (6.3 tons) on the left side. On the downstream end of the lock the average maximum

transverse forces were 69392.257 N (7.8 tons) on the right side and 56937.237 N (6.4 tons) on the left side.

Longitudinal and transverse hawser forces, 3-min valve. Results from a typical experiment with the 3-min valve operation and a 16.093 m (52.8 ft) lift are shown in Plate 10. The maximum longitudinal hawser force was observed in the first two minutes of the filling cycle. Results show that immediately after opening the filling valve the barge encountered a downstream hawser force that was maintained longer than the one experienced with the 1.5-min valve, and then an upstream force followed it. These fluctuations between upstream and downstream forces continued with diminishing magnitudes until the forces were not noticed. The average of the maximum longitudinal hawser forces was 88074.788 N (9.9 tons) in the downstream direction and 62275.103 N (7 tons) in the upstream direction. The average maximum transverse hawser forces measured on the upstream end of the lock chamber were 24910.041 N (2.8 tons) on the right side and 28468.618 N (3.2 tons) on the left side. The average maximum transverse hawser forces measured on the downstream end of the lock chamber were 28468.618 (3.2 tons) on the right side and 22241.108 N (2.5 tons) on the left side. The average maximum longitudinal and transverse hawser forces are shown in Plate 7.

Longitudinal and transverse hawser forces, 7-min valve. Results from a typical experiment with a 7-min valve operation and with a lift of 16.093 m (52.8 ft) are shown on Plate 11. The temporal directional variation in the longitudinal hawser forces was similar to those measured with the 3-min valve operation. The magnitudes were less. The average of the maximum longitudinal hawser forces measured with the 7-min valve was 37365.0616 N (4.2 tons) in the downstream direction and 40923.639 N (4.6 tons) in the upstream direction. The average of the maximum transverse hawser forces measured on the upstream end of the lock chamber was 18682.531 N (2.1 tons) on the right side and 21351.464 N (2.4 tons) on the left side. The average of the maximum transverse hawser forces measured on the downstream end of the lock chamber was 18682.531 N (2.1 tons) on the right side and 22241.108 N (2.5 tons) on the left side. The average maximum longitudinal and transverse hawser forces are shown in Plate 7.

Longitudinal and transverse hawser forces, 11.72-min valve. Results from a typical experiment with a 11.72-min valve operation and a lift of 16.093 m (52.8 ft) are shown on Plate 12. The temporal directional variation in the longitudinal hawser forces was similar to those measured with the 7-min valve operation. Again, the magnitudes were less. The average of the maximum longitudinal hawser forces measured with the 11.72-min valve was 21351.464 N (2.4 tons) in the downstream direction and 27578.974 N (3.1 tons) in the upstream direction. The average of the maximum transverse hawser forces measured on the upstream end of the lock chamber was 16903.242 N (1.9 tons) on the right side and 16903.242 N (1.9 tons) on the left side. The average of the maximum transverse hawser forces measured on the downstream end of the lock chamber was 15123.953 N (1.7 tons) on the right side and 22241.108 N (2.5 tons) on the left side. The average maximum longitudinal and transverse hawser forces are shown in Plate 7. Plates 13 and 14 show the average maximum

hawser forces determined for lifts of 13.716 m and 17.374 m (45 and 57 ft), respectively, during selected filling operations.

Emptying operations

Hawser force measurements and emptying times were also determined with the 1.5-, 3.0-, 7.0-, and 11.72-min valve operations for 16.093, 13.716, and 17.374-m (52.8, 45, and 57-ft) lifts. Plates 15-17 show the average maximum hawser forces measured for different lifts during emptying operations. The hawser force magnitudes were considerably lower than those measured during the filling cycle. The average maximum longitudinal hawser forces measured with the 1.5-min valve and a lift of 16.093 m (52.8 ft) was 80067.989 N (9 tons) in the downstream and upstream directions.

Type 2 chamber design

The original design included a "man port" located on both sides of the downstream end of the lock chamber, past the last set of multiports. The man port was designed to facilitate access of maintenance personnel into the culverts (Plate 18). These ports were later closed (Type 2 chamber design) and experiments were conducted to assess the impact of the closure. The average maximum hawser forces determined from filling and emptying operations are provided in Plates 19 and 20 for the 16.093-m (52.8-ft) lift. The average maximum longitudinal downstream hawser force was 192163.174 N (21.6 tons), and the average maximum upstream hawser force was 187714.952 N (21.1 tons) with a 1.5-min valve. The average maximum transverse hawser forces measured with the 1.5-min valve on the upstream end of the lock were 56047.592 (6.3 tons) on the right side and 62275.103 N (7.0 tons) on the left side. The average maximum transverse hawser forces measured with the 1.5-min valve on the downstream end of the lock was 46261.505 N (5.2 tons) on the right side and 40033.995 N (4.5 tons) on the left side. These results show little change to the longitudinal hawser force measurements related to the closure of the man port.

Pressure measurements

Instantaneous pressure measurements were conducted using pressure cells mounted on the roof of the culvert 11.278 m (37 ft) downstream from the left filling valve (sta 1+93.3) and also downstream from the right emptying valve at sta 12 + 92.4 (Plate 1). High velocities that occur with partial gate openings can cause low pressures downstream of the valve, which, if low enough, can result in cavitation damage. Time-histories of the pressure just downstream of the filling valves for typical filling operations with 1.5-, 3.0-, 7.0-, and 11.72-min valve times are shown in Plates 21-24, respectively. The culvert roof elevation downstream from the filling and emptying valve was 90.526 m (297 ft). The pressures measured downstream of the valve indicate the piezometric grade line elevation is below the roof culvert elevation in every valve operation tested. The time that the pressure is below the roof culvert depends on the valve speed. In

general, the faster the valve the less time the pressure stayed below the roof culvert elevation. Results show that the average minimum pressure was approximately -4.572 m (-15-ft) with the 3.0-min valve. Operation of the lock filling and emptying system with pressures lower than -3.658 m (-12 ft) should be done with caution and proper ventilation should be provided. Prototype experiments are needed to establish the air demand necessary to increase the pressures in the culvert downstream of the valve and establish operational procedures. Time-histories of the pressure just downstream of the emptying valves for typical emptying operations with 1.5-, 3.0-, 7.0-, and 11.72-min valve times are shown on Plates 25-28, respectively. Results show that the average minimum pressure was approximately 3.353 m (-11 ft) with the 7.0-min valve.

Filling times

The filling times reported hereafter refer to the original chamber design (man port open), unless otherwise specified. Experiments demonstrated that there was no significant difference between the original chamber design and the type 2 chamber design.

Filling time, 1.5-min valve. As mentioned previously, the lock water-surface elevation was determined during the filling operation by averaging the piezometric head recorded by pressure cells mounted on the middle and both ends of the lock floor. The filling curve determined for the original chamber design for a typical experiment with an upper pool el 357, a lower pool el 304.2, and a 1.5-min valve-opening operation is shown in Plate 9 along with the hawser data. The average filling time with the 1.5-min valve operation determined from several experiments is shown in Plate 29 along with the average filling time determined with 3.0-, 7.0-, and 11.72-min valve schedules. The average filling time with the 1.5-min valve opening was 13.2 min. . The average filling time determined for the original design with an upper pool el 357, a lower pool el of 304.2, and a 3.0-min valve-opening operation was 14.0 min. The average filling time determined for the original design with an upper pool el 357, a lower pool el of 304.2, and a 7.0-min valve-opening operation was 16.3 min. The average filling time determined for the original design with an upper pool el 357, a lower pool el of 304.2, and a 11.72-min valve-opening operation was 18.9 min.

Emptying times

The emptying times for the 1.5-, 3.0-, 7.0-, and 11.72-min valve operations with an upper pool el 357 and a lower pool el 304.2 were 17, 17.5, 19.3, and 21.3 min, respectively.

4 Hawser Force Measurements for Tows Moored in Downstream Lock Approach

Type 1 Downstream Guard Wall Design (Original)

Experiments were conducted next to measure hawser forces for a three-by five-barge arrangement moored in the lower lock approach during the emptying operation.

Measurements were made in the lower approach using a strain-measuring device connected to the center of the upstream end of the three-by-five barge arrangement (Plate 30). The only measurement made during the course of the experiments was the longitudinal hawser force exerted on the barge. Transverse hawser forces were not measured because of equipment and modeling constraints. Care should be taken not to discard the transverse loads, in some cases these forces could be greater than or equal to the longitudinal hawser forces experienced in these mooring situations, producing a greater than expected resultant force.

The barge was kept in place by attaching the load cell in the upstream end and a secured cable on the downstream end of the barge. The cable was tightened and a preload was applied to the load cell before the emptying cycle started. This prevented any movement of the barge before the beginning of the experiment and provided a measurement of compression forces.

The barge was moored at sta 14+33, sta 15+62.5, and sta 17+60.25 (Plate 30). Upper pool and lower pool combinations ranged from el 354 to el 359 and el 302 to el 314 respectively, and several emptying valve times were used to conduct the experiments. The results from these experiments are shown in Plates 31-33.

Literature review on these type of force measurements revealed no guidance to establish an acceptable range of loads. A field study led by ERDC and the Nashville District was conducted on the lower approach of the existing Kentucky

Lock to measure the hawser loads that tows were experiencing at the project (Sanchez 1998). The study showed that with forces lower than 177928.865 N (20 tons), no adverse conditions were observed. Based on Sanchez (1998), the 177928.865-N (20-ton) limit was the target for acceptable load ranges measured in the physical model.

Plates 31-33 show that with a valve time between 3 min and 11.72 min, sta 17+60.25 could yield acceptable longitudinal hawser forces for the full range of HW/TW combinations. This station would place the barge 115.824 m (380 ft) downstream from the lower miter gates pintle.

Type 2 Downstream Guard Wall Design (Extended)

Experiments were conducted next to assess changes in the forces due to a design change to the downstream guard wall. The type 2 downstream guard wall design included a 60.96-m (200-ft) extension of the riverside wall to facilitate the maintenance of the interlaced lateral discharge system (see Figure 9 and Plate 34).

Plate 35 shows the results of hawser force experiments for valve operations with HW el 357 and TW el 304.2 and the type 2 downstream guard wall design. The results demonstrate that the wall extension increased the forces considerably and that the barges would have to be moored farther downstream from the lower miter gates than with the original design. The maximum longitudinal hawser force measured at sta 17+60.25 was 756197.675 N (85 tons). This exceeded the desired load.

Type 3 Downstream Guard Wall Design (New)

Experiments were conducted to evaluate the type 3 downstream guard wall design (Plate 36). The design was a modification to the original design that included a smooth transition to the guard wall nose on both the riverside and the landside. Plate 37 shows the maximum longitudinal hawser force measured at sta 17+60.25 with different valve times. Results demonstrate that the type 3 design increased the longitudinal hawser forces in comparison with the original design, but the forces were kept in an acceptable range. The maximum longitudinal hawser force measured at sta 17+60.25 with a 7-min valve time was 142343.092 N (16 tons).

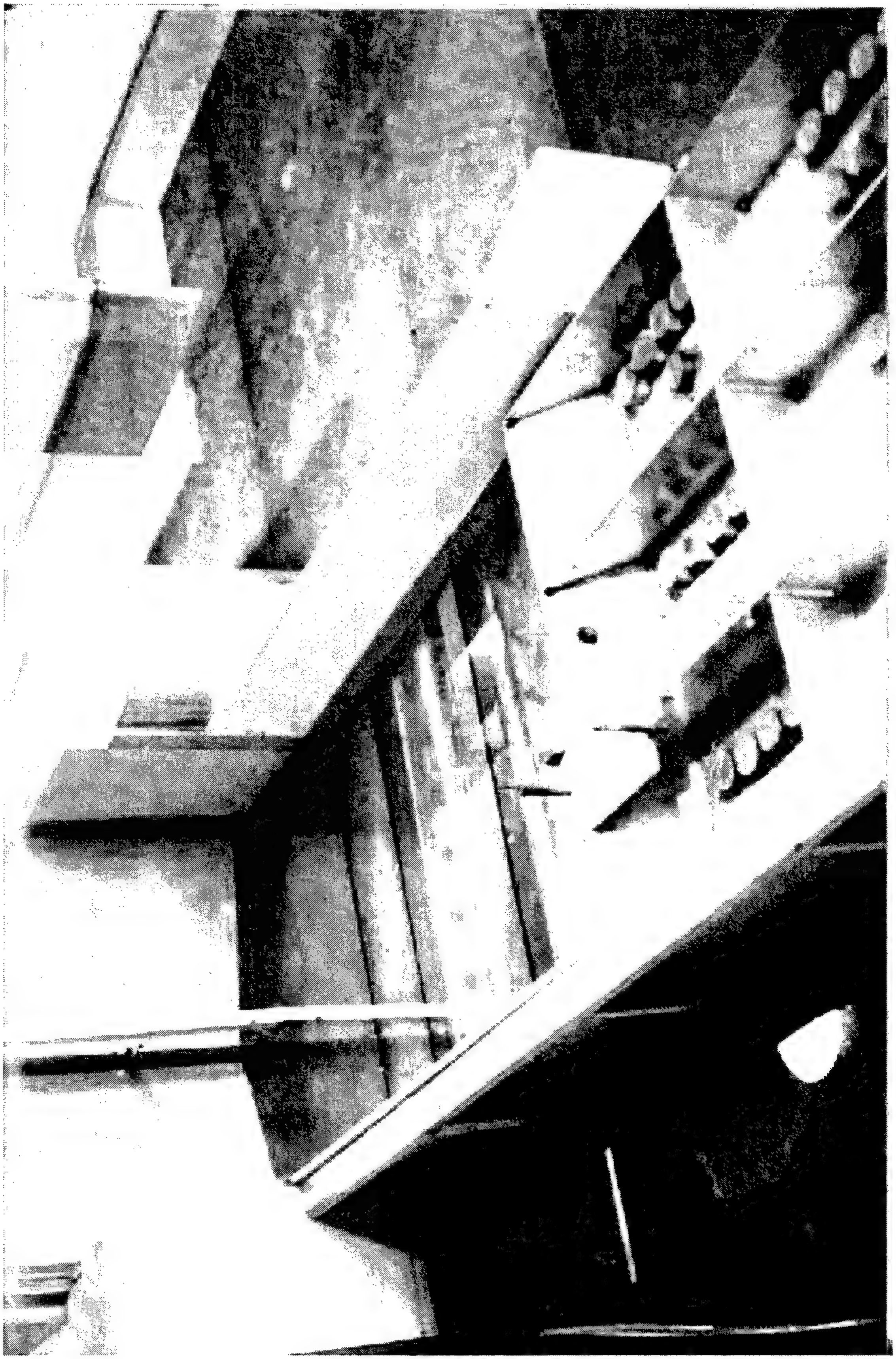

Figure 9. Downstream lock approach, hawser load measurement with type 2 DS guard wall design (US view)

5 Hawser Force Measurements for Tows Moored in Upstream Lock Approach

Experiments were conducted next to measure hawser forces for a three-by five-barge arrangement moored in the upstream lock approach. The load cell device, discussed previously, was used to measure the longitudinal hawser forces on a tow moored to the upstream floating guide wall during the filling operations. The barge arrangement was moored 60.96 m (200 ft) upstream of the upper miter gates pintle (see Figures 10-11 and Plate 38).

Longitudinal hawser forces. Results from a typical experiment with the 1.5-min valve operation and 16.093-m (52.8-ft) lift are shown in Plate 39. The longitudinal hawser force indicates that immediately after the valve begins to open, the barge in the upper lock approach experienced a downstream hawser force during the entire filling operation. Between 1 and 3 min into the filling cycle, the hawser force reached a maximum value of 124550.205 N (14 tons). The longitudinal hawser force then begins to reduce in magnitude with time.

The average maximum hawser forces measurements made for an upper pool el of 357 and a lower pool el of 304.2 for 1.5- and 7.0-min valves are shown in Plate 40. Experiments were repeated to ensure consistency. The average of the maximum longitudinal hawser forces measured with the 1.5 min valve was 128998.427 N (14.5 tons) in the downstream direction. These longitudinal hawser forces were considered acceptable.

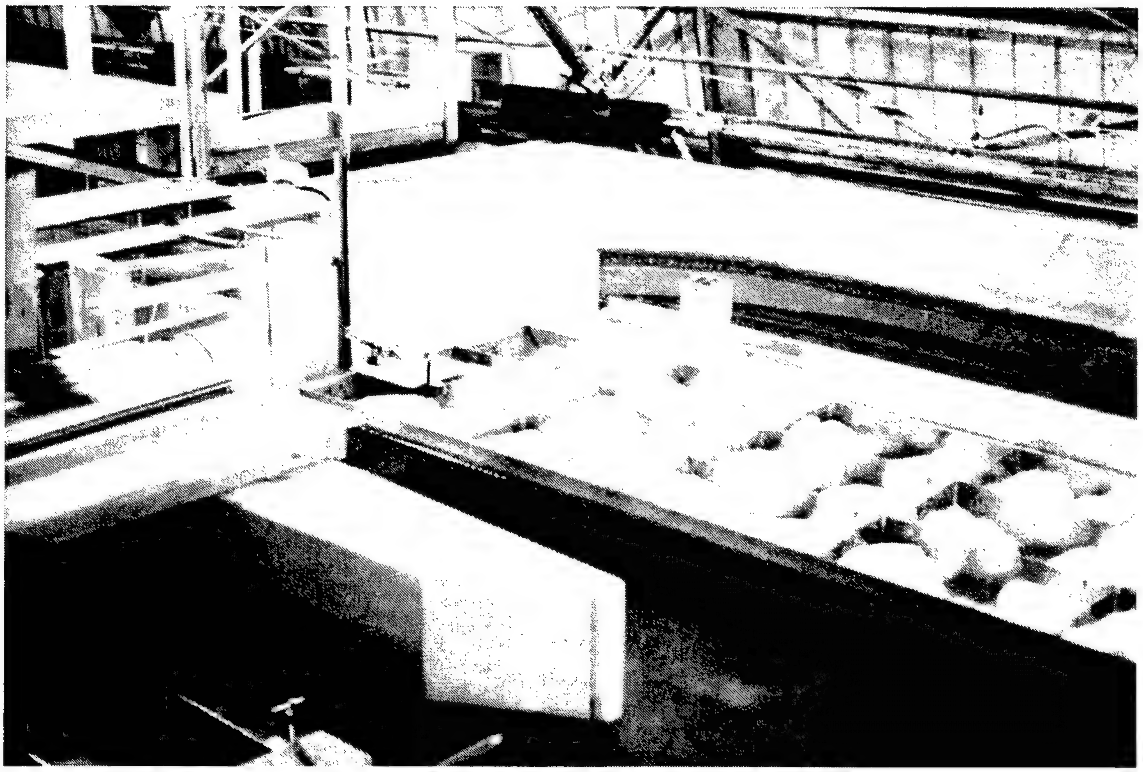

Figure 10. Upstream lock approach, hawser load measurement model setup (DS view)

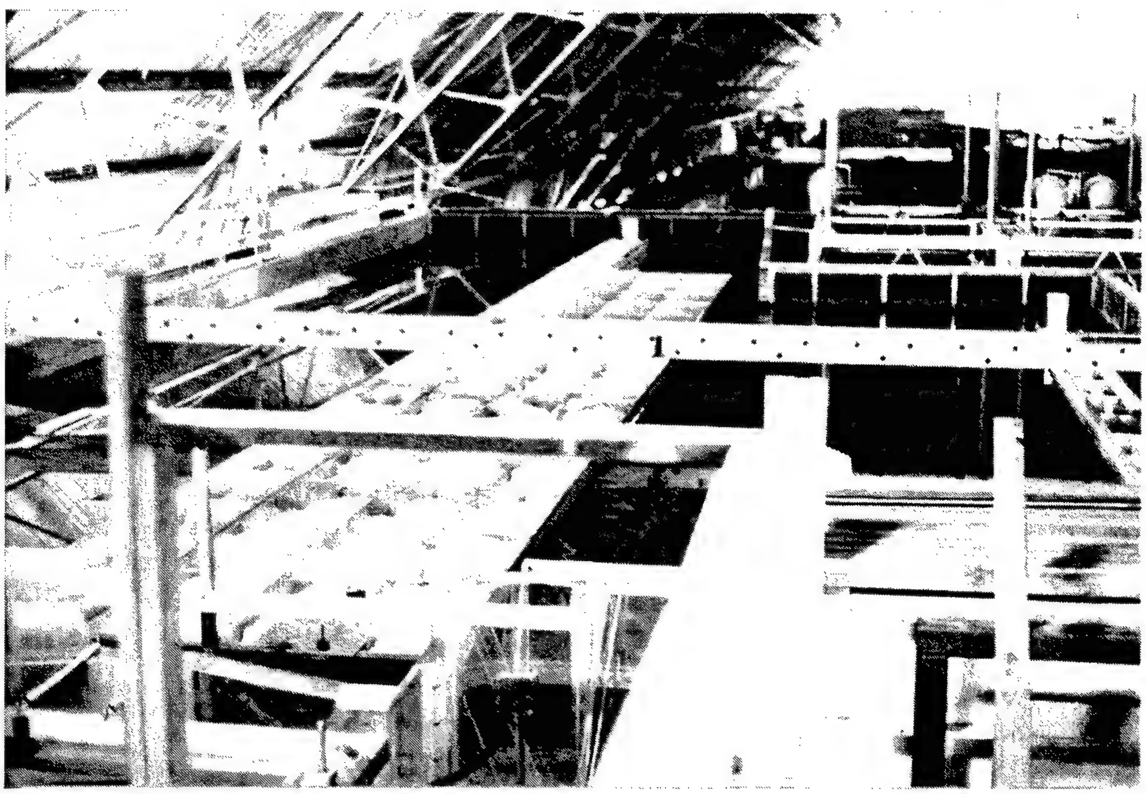

Figure 11. Upstream lock approach, hawser load measurement model setup (US view)

6 Summary and Conclusions

Summary

A 1:25 scale model of the proposed Kentucky Lock Addition was constructed to evaluate the lock filling and emptying system performance and flow conditions in the upper and lower approaches. Modifications to the upstream lock approach were made to reduce the strength of vortices observed during filling operations. The flow conditions in the upper approach were improved with the type 5 approach design shown on Plate 6. The flow patterns in the lock approach were enhanced and flow instabilities were not noticed. Small vortices should be expected during the filling operations.

Model experiments with the original chamber design revealed the performance was acceptable with the 7.0-min valve operation for the filling cycle and the 3.0-min valve operation for the emptying cycle. Both valve operations resulted in maximum hawser forces under 44482.216 N (5 tons) for the 16.093-m (52.8-ft) lift. A type 2 chamber design was also tested, but no significant reductions or increases were observed. Consequently, the type 1 (original) chamber design was considered acceptable. No changes were made to the interlaced lateral discharge system design.

Experiments were performed to measure hawser forces for a three-by five-barge arrangement moored in the lower lock approach during the emptying operation. Results showed that the type 3 downstream guard wall design increased the longitudinal hawser forces slightly in comparison with the original guard wall design, but the forces were kept in an acceptable range. These tolerable longitudinal hawser forces were experienced at sta 17+60.25 with a 7.0-min valve operation during the emptying cycle. It should be noted that transverse forces were neglected and they could be a significant component in the resultant forces experienced in the prototype.

Experiments were also performed to measure hawser forces for a three-by five-barge arrangement moored in the upstream lock approach. The barge arrangement was moored 60.96 m (200 ft) upstream of the upper miter gates pintle (Plate 38). The maximum longitudinal hawser forces measured with a 16.093-m (52.8-ft) lift and a 1.5-min valve operation during the filling cycle were inside an acceptable range.

Conclusions

The model investigation revealed that:

a. Modifications to the upper lock approach improved flow conditions in the area.

b. Vortices in the upstream approach are acceptable with the type 5 approach design.

c. To achieve acceptable hawser forces in the chamber, the filling valves should not be opened in less than 7 min. The emptying valves could be opened in 3 min.

d. Original design chamber performance was acceptable if filling times of 16.3 min and emptying times of 17.5 min are feasible.

e. Prototype experiments are needed to establish the air demand necessary to increase the pressures in the culvert downstream of the valve and establish operational procedures.

f. Tows should moor in the lower approach at sta 17+60.25 with the type 3 downstream guard wall design.

g. Tows should moor to the floating guide wall at least 60.96 m (200 ft) from the upper miter gates pintle during filling operations.

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Table 1 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 114.3 m (375 ft)
Tailwater Elevation = 94.49 m (310 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	78
	0	80
	1	89
	0	99
2	1	100
	0	117
	2	161
	0	184
3	1	94
	2	96
	1	101
	0	112
4	1	75
	2	85
	1	95
	0	100
	2	111
	0	119
	1	131
	0	135
5	1	105
	2	110
	0	137
	1	140
	0	142
	1	156
	0	180

Table 2 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 114.3 m (375 ft)
Tailwater Elevation = 94.49 m (310 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	0	0
2	1	100
	0	117
	2	161
	0	184
3	2	160
	0	165
	1	178
	0	183
4	0	0
5	0	0

Table 3 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.728 m (360 ft)
Tailwater Elevation = 91.44 m (300 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	69
	2	72
	0	77
2	1	66
	0	74
	1	120
	2	127
	1	131
	2	136
	0	138
3	1	70
	0	80
4	1	67
	2	75
	1	77
	0	81
5	0	0

Table 4 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.728 m (360 ft)
Tailwater Elevation = 91.44 m (300 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	90
	0	93
	1	102
	2	108
	1	110
	2	113
	0	120
2	0	0
3	1	107
	2	109
	1	115
	0	118
4	1	82
	0	90
	1	95
	2	99
	0	110
5	1	74
	2	76
	0	85
	2	108
	0	112

Table 5 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 98.389 m (322.8 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	0	0
2	1 2 0 1 2 1 0	75 84 89 92 94 98 103
3	0	0
4	0	0
5	1 2 1 2 0	79 95 97 99 105

Table 6 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 98.389 m (322.8 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	0	0
2	0	0
3	2 1 0	123 126 134
4	1 2 1 0	117 120 141 147
5	1 0	103 138

Table 7 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 92.72 m (304.2 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1 2 1 2 0 1 0	72 75 78 84 88 97 107
2	1 2 0	82 86 90
3	0	0
4	1 0	89 103
5	1 0	77 87

Table 8 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 92.72 m (304.2 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	0	0
2	1 2 1 2 1 0	78 99 105 110 117 118
3	1 2 1 0	85 90 94 95
4	1 2 1 2 0	78 90 93 103 115
5	1 2 1 0	100 107 115 123

Table 9 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	60
	0	65
2	1	82
	0	84
3	1	53
	0	60
	1	75
	0	79
	1	82
	0	83
	1	125
	0	127
4	1	53
	0	55
	1	72
	2	77
	0	86
5	1	56
	2	58
	0	62
	1	76
	2	80
	1	82
	0	85
	1	139
	2	145
	1	150
	0	154

Table 10 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	79
	2	82
	1	85
	0	88
2	1	89
	2	93
	1	96
	2	99
	1	102
	0	107
3	1	90
	2	92
	0	104
4	1	93
	2	97
	1	106
	0	109
	1	152
	0	156
	1	164
	0	180
5	1	122
	0	132

Table 11 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	2	39
	3	60
	4	64
	2	69
	3	80
	5	111
	3	122
	0	126
2	1	41
	2	45
	0	50
	1	64
	2	66
	4	70
	0	75
	2	79
	3	93
	2	99
	3	101
	2	115
	3	119
	2	126
	0	140
3	1	59
	2	62
	3	65
	2	78
	3	80
	4	81
	2	86
	3	93
	3	98
	2	117
	0	120
4	1	60
	2	66
	0	75
	2	79
	3	109
	2	117
	0	120
	1	127
	2	131
	0	138
5	2	70
	0	84
	1	110
	0	123
	2	131
	0	140
	2	146
	0	153

Table 12 – Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	70
	2	72
	1	80
	2	85
	1	91
	2	93
	1	101
	2	117
	1	128
	2	137
	0	159
2	1	66
	2	72
	1	85
	2	89
	3	102
	2	105
	3	110
	2	118
	1	135
	0	144
3	2	61
	1	66
	2	77
	0	82
	2	85
	0	110
	1	125
	0	128
	1	168
	0	176
4	1	66
	2	69
	0	73
	1	78
	2	90
	1	100
	0	110
	1	120
	2	134
	1	145
	2	150
	1	155
	0	160
5	1	69
	2	72
	0	80
	1	89
	2	91
	3	95
	2	97
	1	99
	0	104
	1	115
	0	124
	1	148
	0	171

Table 13 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 108.814 m (357 ft)
Tailwater Elevation = 92.72 m (304.2 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	2 0	70 105
2	1 2 0	64 67 103
3	2 0 2 0	41 46 52 56
4	2 0 2 3 2 3 0 2 0	42 48 55 64 80 100 111 120 140
5	2 0 2 3 2 0 2 1 0	57 59 62 70 75 97 106 153 155

Table 14 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 108.814 m (357 ft)
Tailwater Elevation = 92.72 m (304.2 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	69
	2	73
	0	80
	1	87
	2	89
	2	99
	1	102
	2	105
	1	123
	2	133
	0	138
2	1	86
	2	91
	1	107
	0	110
3	2	93
	3	95
	0	100
	1	136
	2	140
	0	168
4	2	78
	1	82
	2	93
	1	102
	0	105
	2	133
	1	155
	0	157
5	1	80
	2	89
	3	95
	1	98
	2	100
	1	102
	2	105
	0	115

Table 15 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 105.46 m (346 ft)
Tailwater Elevation = 94.488 m (310 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	26
	2	32
	4	38
	2	42
	1	50
	2	58
	0	120
2	1	24
	2	29
	0	35
	2	49
	1	107
	0	125
3	2	35
	0	44
	2	63
	3	80
	2	81
	1	103
	0	116
4	2	33
	3	35
	0	36
	2	41
	4	44
	0	49
	2	60
	3	80
	0	88
	0	93
	2	109
	0	
5	2	45
	1	85
	0	103

Table 16 - Vortex Experiments, Type 1 Approach Design

Headwater Elevation = 105.46 m (346 ft)
Tailwater Elevation = 94.488 m (310 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	44
	2	65
	1	70
	2	77
	3	84
	1	87
	2	94
	3	96
	1	98
	0	120
2	1	50
	2	54
	0	71
	1	72
	2	85
	1	87
	0	120
3	2	48
	1	85
	2	95
	0	98
	2	104
	3	108
	2	110
	0	119

Table 17 - Vortex Experiments, Type 2 Approach Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	48
	2	50
	3	72
	4	75
	2	80
	3	85
	2	87
	3	98
	4	100
	5	124
	2	130
	0	
2	1	48
	2	58
	3	70
	2	74
	3	96
	4	100
	5	111
	0	118
	2	125
	0	135
3	1	66
	2	70
	3	74
	4	75
	2	79
	3	95
	4	97
	5	113
	3	120
	2	123
	0	131
4	4	50
	2	67
	3	88
	2	120
	0	150
5	2	49
	3	56
	0	65
	2	69
	3	74
	4	86
	5	94
	4	100
	3	110
	0	123
6	3	60
	4	80
	2	86
	1	132
	2	139
	0	150

Table 18 - Vortex Experiments, Type 2 Approach Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
4.5-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	2	80
	3	90
	2	94
	4	103
	3	108
	4	111
	5	120
	2	137
	0	138
2	2	77
	3	85
	2	92
	3	96
	4	99
	3	102
	5	108
	3	110
	2	118
	3	120
	2	132
	0	180
3	2	77
	3	93
	2	95
	3	98
	2	99
	3	109
	2	114
	0	120
	2	138
	0	159
4	1	89
	2	93
	3	105
	2	109
	1	124
	0	132
	2	173
	0	174
5	2	59
	0	67
	1	79
	2	81
	5	88
	0	93
	2	97
	3	100
	4	109
	3	113
	4	120
	3	128
	2	140
	0	157

Table 19 - Vortex Experiments, Type 2 Approach and Type 1 Curtain Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
First Depth = 10'		
1	2	68
	4	80
	3	104
	4	110
	0	116
Second Depth = 20'		
1	1	48
	2	53
	3	64
	0	70
	1	83
	2	89
	4	98
	3	103
	4	106
	3	110
	4	117
	3	119
	2	126
	0	127
Third Depth = 36'		
1	3	47
	4	50
	0	52
	2	59
	1	114
	2	134
	0	136
2	2	47
	0	66
	2	89
	0	100
3	2	59
	3	120
	0	132
4	1	50
	2	55
	3	66
	2	70
	3	99
	2	104
	1	115
	2	136
	0	149

Table 20 - Vortex Experiments, Type 2 Approach and Type 2 Curtain Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 $\times$15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1	53
	2	64
	3	120
	2	147
	0	153
2	1	45
	2	58
	3	79
	2	81
	0	94
	1	126
	2	140
	0	150
	2	157
	0	164
3	1	57
	2	60
	3	67
	2	69
	0	114
4	2	59
	3	69
	0	72
	2	87
	3	94
	2	117
	0	130
5	2	57
	3	67
	0	71
	2	80
	4	89
	2	93
	0	100

Table 21 - Vortex Experiments, Type 3 Approach Design

Headwater Elevation = 107.9 m (354 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.0-min valve, 15 × 15 Intake Culvert Design

Experiment Number	Vortex Type	Model Time (sec)
1	1 2 0 2 1 0	60 95 100 118 120 135
2	1 2 0	54 60 80
3	1 2 0 2 0	55 59 85 125 130
4	2 0 2 0 2 0	66 75 108 113 135 144
5	1 2 0 2 0 2 0	44 51 79 89 99 132 145
6	2 0	72 88
7	2 0 2 0 1 0	70 79 100 113 126 129

Table 22	Type 4 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
1	1	38
	0	43
	1	45
	2	47
	0	52
	1	72
	0	74
2	1	40
	0	47
	1	55
	0	56
	1	75
	2	77
	0	80
	1	87
	2	90
	3	92
	0	100
	1	117
	0	122
3	1	42
	2	47
	0	52
	1	67
	0	69
	1	97
	0	98
	1	107
	0	109
4	1	42
	0	43
	1	47
	0	49
	1	60
	0	62
	1	67
	0	69
	1	80
	0	87
	1	97
	0	99
5	1	47
	0	52
	1	56
	0	58
	1	75
	0	76
	1	87
	0	88
	1	102
	0	104
	1	112
	0	113
	1	122
	0	124

Table 23	Type 4 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
1	1	75
	0	89
	1	107
	2	108
	0	109
	1	142
	0	149
2	1	87
	0	100
	1	107
	2	109
	0	110
	1	127
	0	129
	1	147
	0	149
3	1	80
	0	85
	1	89
	0	92
	1	97
	2	104
	0	107
	1	125
	0	127
4	1	84
	0	86
	1	97
	2	102
	0	103
	1	117
	0	119
	1	123
	0	124
	1	152
	0	154
5	1	88
	0	96
	1	97
	2	99
	0	100
	1	122
	0	123
	1	129
	0	130
	1	139
	0	140
	1	147
	0	150

Table 24 Type 4 Approach Design

Headwater Elevation = 107.9 m (359 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
1.5-min Valve

Experiment Number	Vortex Type	Model Time (sec)
1	1	47
	0	49
	1	55
	0	56
	1	62
	2	67
	0	72
	1	82
	0	84
2	1	42
	0	46
	1	50
	0	52
	1	53
	2	54
	0	57
	1	69
	2	72
	0	75
	1	90
	0	92
3	1	42
	0	47
	1	48
	0	50
	1	57
	0	60
	1	69
	0	73
	1	77
	2	82
	3	87
	4	92
	0	96
	1	105
	0	106
4	1	45
	0	48
	1	52
	0	53
	1	60
	0	62
	1	67
	2	72
	3	77
	0	82
	1	87
	0	89
	1	95
	0	96

Table 24 Cont.	Type 4 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
5	1	42
	0	47
	1	49
	2	52
	0	54
	1	75
	0	76
	1	82
	0	84
	1	94
	0	96
	1	122
	0	124
6	1	40
	0	42
	1	45
	0	50
	1	56
	2	60
	3	62
	0	66
	1	86
	0	87
	1	122
	0	127

Table 25 **Type 4 Approach Design**

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
7.0-min Valve

Experiment Number	Vortex Type	Model Time (sec)
1	1	94
	0	96
	1	107
	0	109
	1	112
	0	116
	1	123
	0	124
	1	144
	0	146
2	1	95
	0	100
	1	107
	0	109
	1	117
	0	118
	1	132
	0	133
	1	150
	0	152
3	1	92
	0	93
	1	100
	0	102
	1	107
	0	108
	1	115
	0	120
	1	124
	0	126
	1	143
	0	144
4	1	107
	0	108
	1	117
	0	119
	1	122
	0	124
	1	132
	0	134
	0	144
	0	145
	1	155
	0	156

Table 25 (Continued)	Type 4 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
5	1	92
	0	93
	1	98
	0	100
	1	109
	2	110
	0	112
	1	120
	0	122
	1	127
	0	129
	1	153
	0	154

Table 26	Type 5 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
1	1	46
	2	48
	3	55
	0	57
	1	59
	0	60
	1	75
	2	76
	1	77
	0	78
	1	84
	0	85
	1	100
	0	101
	1	115
	0	117
2	1	45
	2	47
	3	50
	2	52
	1	53
	0	55
	1	60
	0	70
	1	71
	2	73
	3	75
	3	85
	2	87
	1	89
	0	90
	1	95
	2	96
	1	97
	0	98
	1	100
	2	102
	3	105
	3	111
	2	113
	1	115
	0	116

Table 26 Cont.	Type 5 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
3	1	45
	2	46
	0	47
	1	60
	2	62
	0	63
	1	70
	2	72
	1	76
	0	77
	1	78
	2	79
	3	80
	2	83
	1	84
	0	85
	1	87
	2	88
	3	89
	1	92
	0	93
4	1	48
	2	50
	1	55
	0	58
	1	60
	0	62
	1	65
	0	67
	1	75
	0	77
	1	83
	0	85
	1	90
	2	92
	1	94
	0	95
	1	115
	2	116
	1	117
	0	118
5	1	48
	2	50
	1	52
	0	53
	1	58
	0	60
	1	65
	0	67
	1	70
	2	71
	0	72
	1	75
	0	77
	1	83
	2	84
	3	85
	1	87
	0	88
	1	108
	0	110

Table 26 Cont.	Type 5 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
6	1	40
	0	41
	1	43
	0	44
	1	45
	0	47
	1	55
	2	56
	0	57
	1	70
	2	71
	1	72
	0	73
	1	75
	2	76
	3	77
	3	84
	2	85
	1	86
	0	87
	1	95
	0	97
	1	104
	0	106

Table 27 Type 5 Approach Design

Headwater Elevation = 109.42 m (359 ft)
Tailwater Elevation = 91.897 m (301.5 ft)
7.0-min Valve

Experiment Number	Vortex Type	Model Time (sec)
1	1	44
	2	45
	0	46
	1	48
	2	49
	0	50
	1	55
	2	56
	1	57
	0	58
	1	65
	2	67
	1	69
	0	70
	1	85
	2	86
	0	87
	1	90
	2	91
	0	92
	1	107
	2	108
	0	109
	1	135
	0	137
2	1	45
	0	46
	1	56
	0	57
	1	70
	0	72
	1	91
	0	100
	1	105
	0	107
	1	118
	2	119
	0	120
	1	125
	2	127
	1	129
	0	130
	1	135
	2	136
	1	137
	0	138
3	1	90
	0	91
	1	95
	0	97
	1	105
	2	107
	3	110
	3	115
	2	117
	1	120
	0	122
	1	133
	2	134

Table 27 Cont.	Type 5 Approach Design	
Headwater Elevation = 109.42 m (359 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
3	1	135
	0	136
	1	140
	0	144
	1	156
	0	158
	1	180
	2	181
	0	182
4	1	48
	0	58
	1	97
	0	125
	1	130
	2	145
	1	150
	0	155
	1	167
	2	170
	1	172
	0	173
	1	175
	2	177
	1	179
	0	180
5	1	95
	2	105
	1	110
	0	113
	1	115
	2	117
	1	118
	0	120
	1	122
	0	125
	1	130
	0	135
	1	136
	0	146
	1	173
	0	175
6	1	91
	0	117
	1	120
	0	132
	1	135
	2	137
	0	140
	1	143
	0	145
	1	150
	0	153
	1	155
	2	157
	3	170
	0	172
	1	185
	0	187

Table 28	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) **Tailwater Elevation = 91.897 m (301.5 ft)** **1.5-min Valve**		
Experiment Number	**Vortex Type**	**Model Time (sec)**
1	1	84
	0	90
	1	95
	0	105
	1	107
	2	109
	0	112
	1	118
	0	123
	1	125
	2	127
	0	130
	1	135
	0	143
	1	145
	0	155
	1	160
	0	170
2	1	105
	2	108
	1	113
	0	115
	1	117
	2	120
	3	123
	3	128
	2	131
	1	133
	0	135
	1	140
	0	155
	1	160
	0	170
	1	177
	0	188
3	1	105
	2	108
	0	110
	1	115
	2	118
	0	120
	1	123
	2	124
	3	125
	0	126
	1	128
	3	130
	4	131
	3	133
	0	135
	1	138
	0	140
	1	142
	0	155

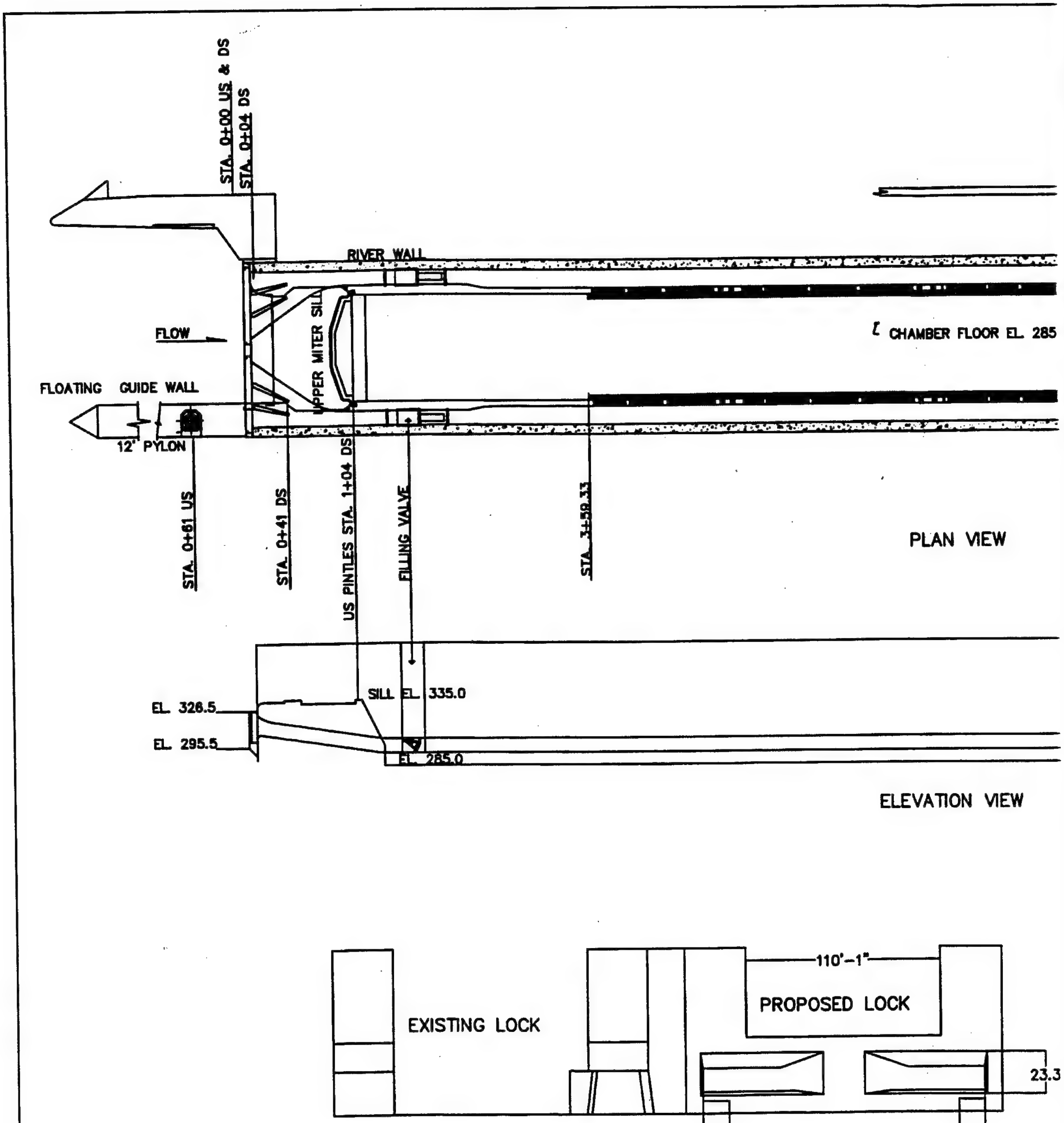
Table 28 Cont.	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
3	1	158
	0	160
	1	165
	0	175
	1	185
	2	187
	1	189
	0	190
4	1	40
	2	44
	1	46
	0	48
	1	53
	2	55
	1	57
	0	60
	1	63
	2	65
	0	67
	1	70
	2	71
	1	72
	0	73
	1	75
	2	76
	0	78
	1	83
	2	84
	0	85
	1	90
	0	95
	1	110
	2	111
	3	112
	2	114
	0	115
	1	123
	0	126
5	1	48
	0	55
	1	58
	2	59
	3	60
	3	75
	2	76
	0	80
	1	85
	0	95
	1	100
	2	102
	0	105
	1	110
	0	113
	1	127
	0	130

Table 28 Cont.	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 1.5-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
6	1	42
	2	45
	0	47
	1	53
	0	57
	1	58
	2	59
	3	60
	3	65
	2	68
	0	70
	1	71
	2	72
	3	73
	3	76
	2	77
	0	78
	1	80
	2	82
	0	83
	1	90
	2	91
	0	93
	1	100
	0	105

Table 29	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
1	1	85
	0	90
	1	93
	0	95
	1	97
	2	98
	3	100
	2	104
	1	106
	0	107
	1	108
	0	114
	1	115
	2	117
	0	119
	1	125
	2	127
	0	130
	1	150
	2	151
	0	153
	1	163
	2	164
	0	166
2	1	80
	0	85
	1	87
	0	90
	1	95
	2	98
	3	99
	3	103
	2	104
	0	105
	1	110
	0	112
	1	117
	2	118
	0	120
	1	125
	2	127
	3	130
	2	132
	1	135
	0	138
3	1	75
	0	80
	1	90
	0	95
	1	98
	2	100
	3	102
	2	111
	1	112
	0	113
	1	118
	2	119
	0	120
	1	125

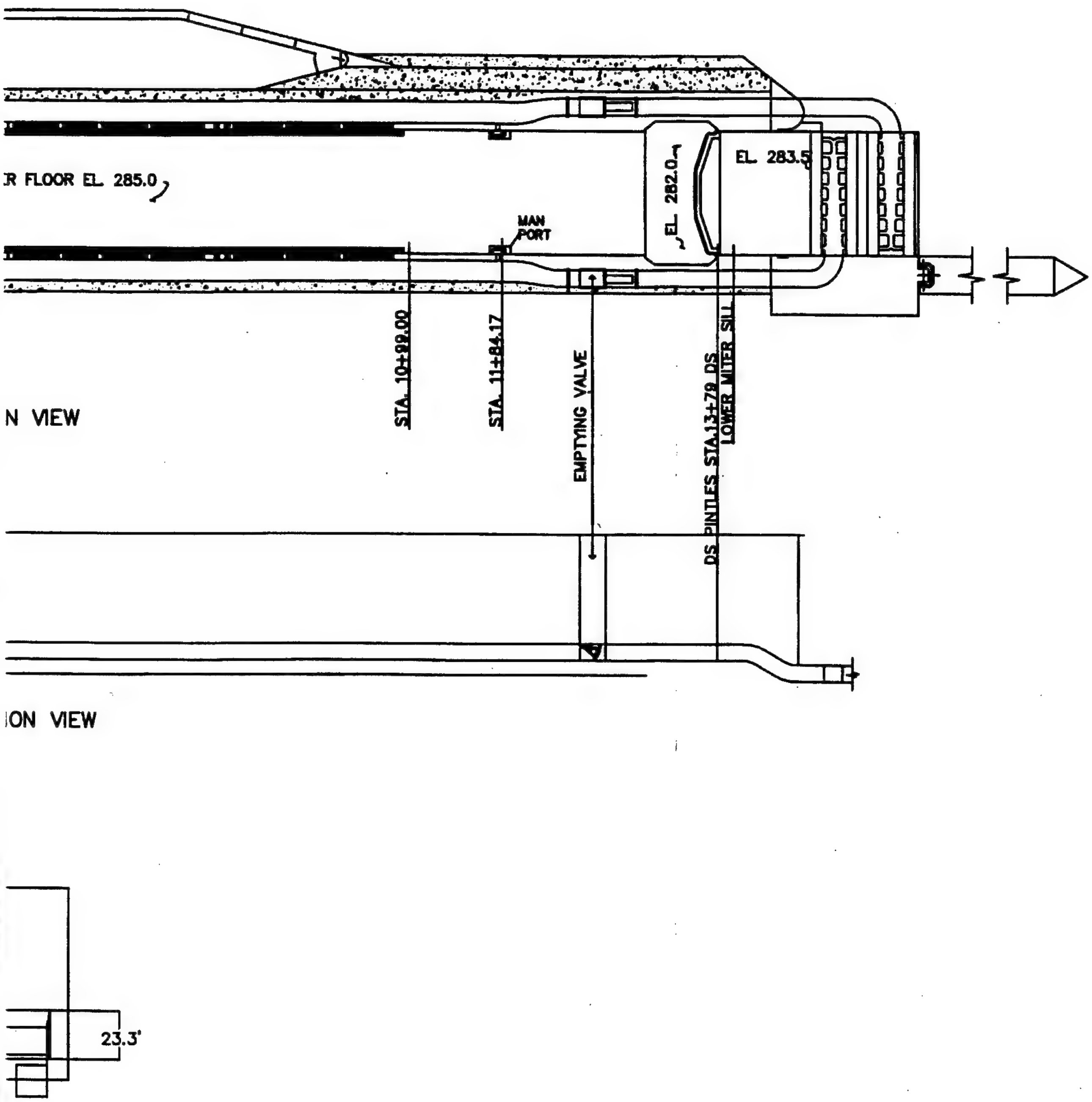
Table 29 Cont.	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
3	2	127
	3	129
	2	133
	1	134
	0	135
	1	155
	2	157
	1	160
	0	163
4	1	87
	0	93
	1	98
	2	100
	1	103
	0	104
	1	105
	2	107
	1	110
	0	111
	1	115
	0	118
	1	125
	2	126
	0	127
	1	140
	0	142
	1	154
	2	156
	1	160
	0	161
5	1	85
	0	87
	1	90
	0	93
	1	95
	2	96
	3	97
	3	109
	2	112
	1	116
	0	118
	1	128
	0	130
	1	138
	2	139
	0	140
	1	145
	2	146
	0	147

Table 29 Cont.	Type 5 Approach Design	
Headwater Elevation = 107.9 m (354 ft) Tailwater Elevation = 91.897 m (301.5 ft) 7.0-min Valve		
Experiment Number	**Vortex Type**	**Model Time (sec)**
6	1	93
	0	95
	1	98
	2	100
	3	103
	2	108
	1	110
	0	111
	1	118
	2	119
	0	120
	1	123
	0	126
	1	130
	0	135
	1	153
	2	154
	0	155



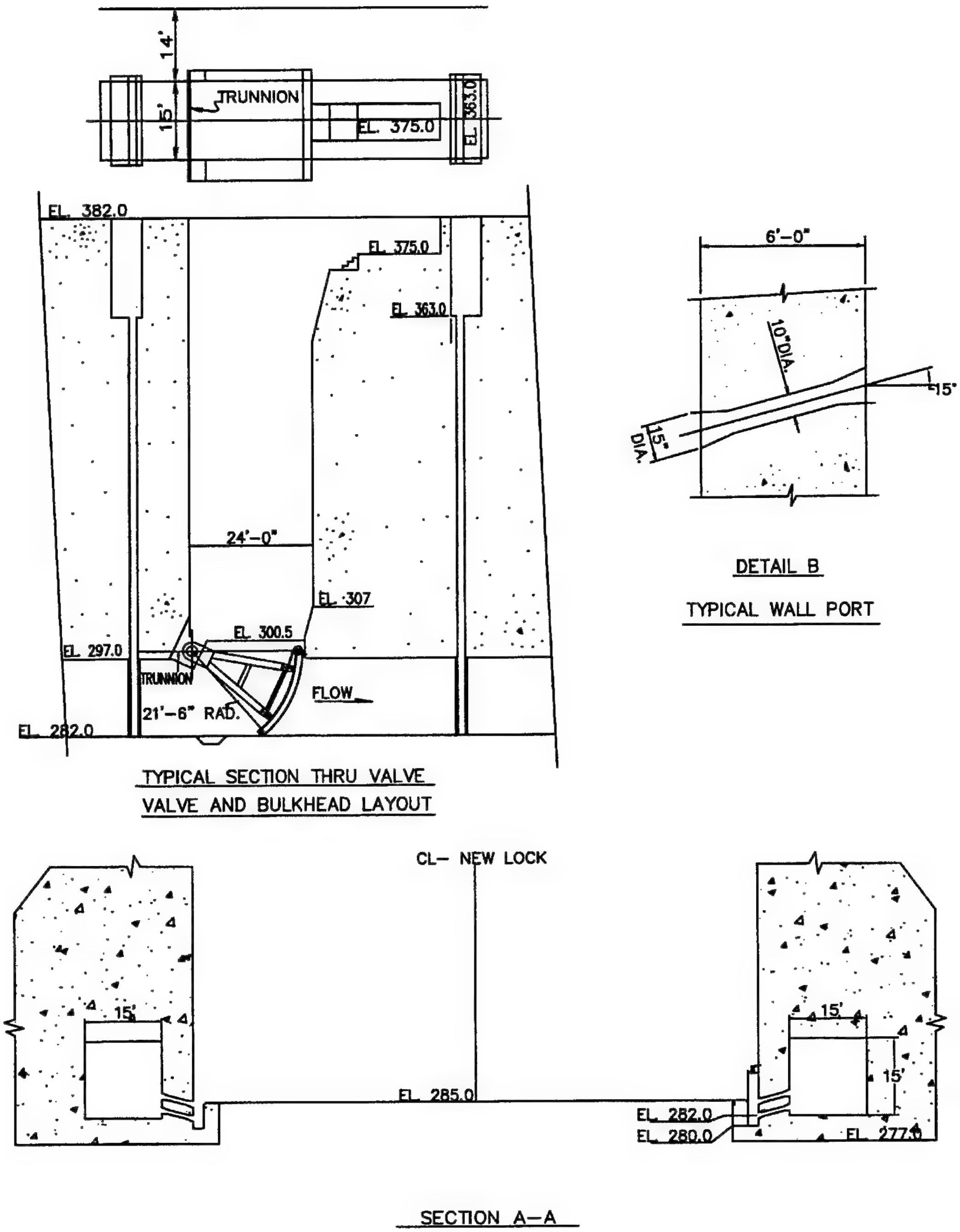
FRONT VIEW OF UPSTREAM INTAKE
STATION 0+04

1



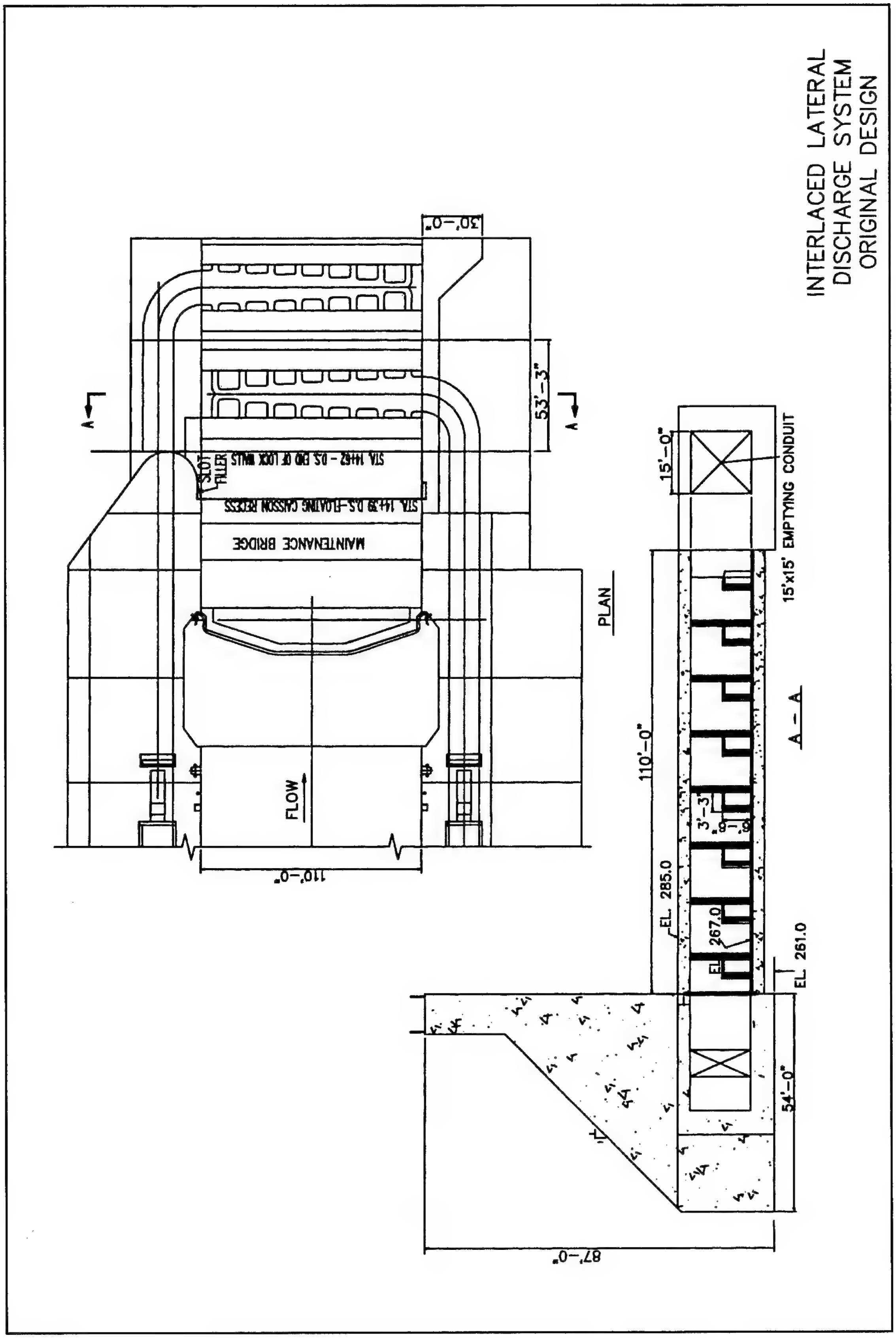
TYPE 1 DESIGN (ORIGINAL)
FILLING AND EMPTYING SYSTEM

2



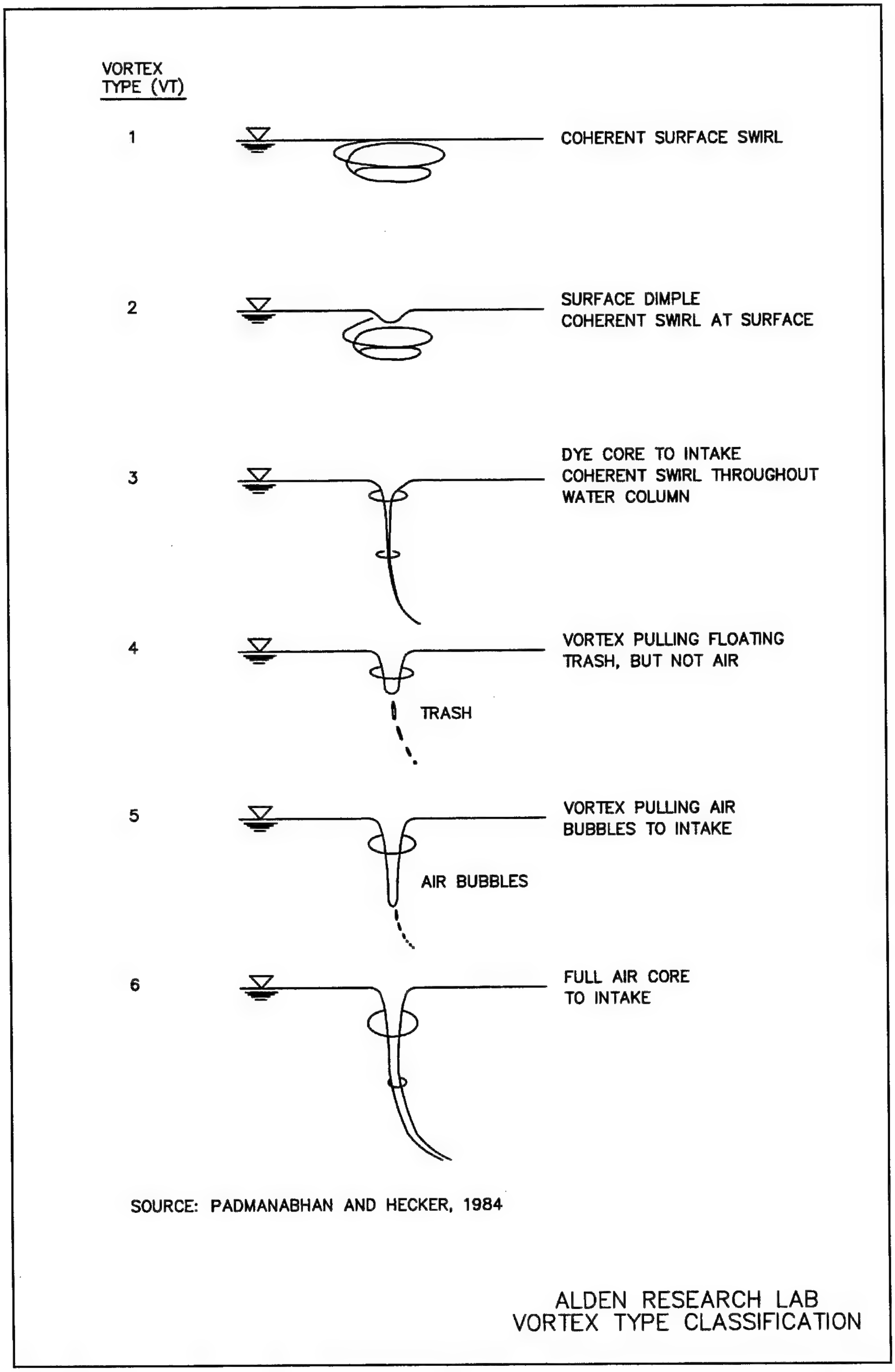
VALVE AND MULTIPORT DETAILS (ORIGINAL DESIGN)

Plate 2



INTERLACED LATERAL DISCHARGE SYSTEM ORIGINAL DESIGN
PLAN
A - A
FLOW
MAINTENANCE BRIDGE
STA. 14+62 - D.S. END OF LOCK WALLS
STA. 14+39 D.S.-FLOATING CAISSON RECESS
SLOT FILLER
110'-0"
30'-0"
53'-3"
15'-0"
15'x15' EMPTYING CONDUIT
EL. 285.0
EL. 267.0
EL. 261.0
3'-3"
54'-0"
87'-0"

Plate 3


VORTEX
TYPE (VT)
1
COHERENT SURFACE SWIRL
2
SURFACE DIMPLE
COHERENT SWIRL AT SURFACE
3
DYE CORE TO INTAKE
COHERENT SWIRL THROUGHOUT
WATER COLUMN
4
VORTEX PULLING FLOATING
TRASH, BUT NOT AIR
TRASH
5
VORTEX PULLING AIR
BUBBLES TO INTAKE
AIR BUBBLES
6
FULL AIR CORE
TO INTAKE
SOURCE: PADMANABHAN AND HECKER, 1984
ALDEN RESEARCH LAB
VORTEX TYPE CLASSIFICATION

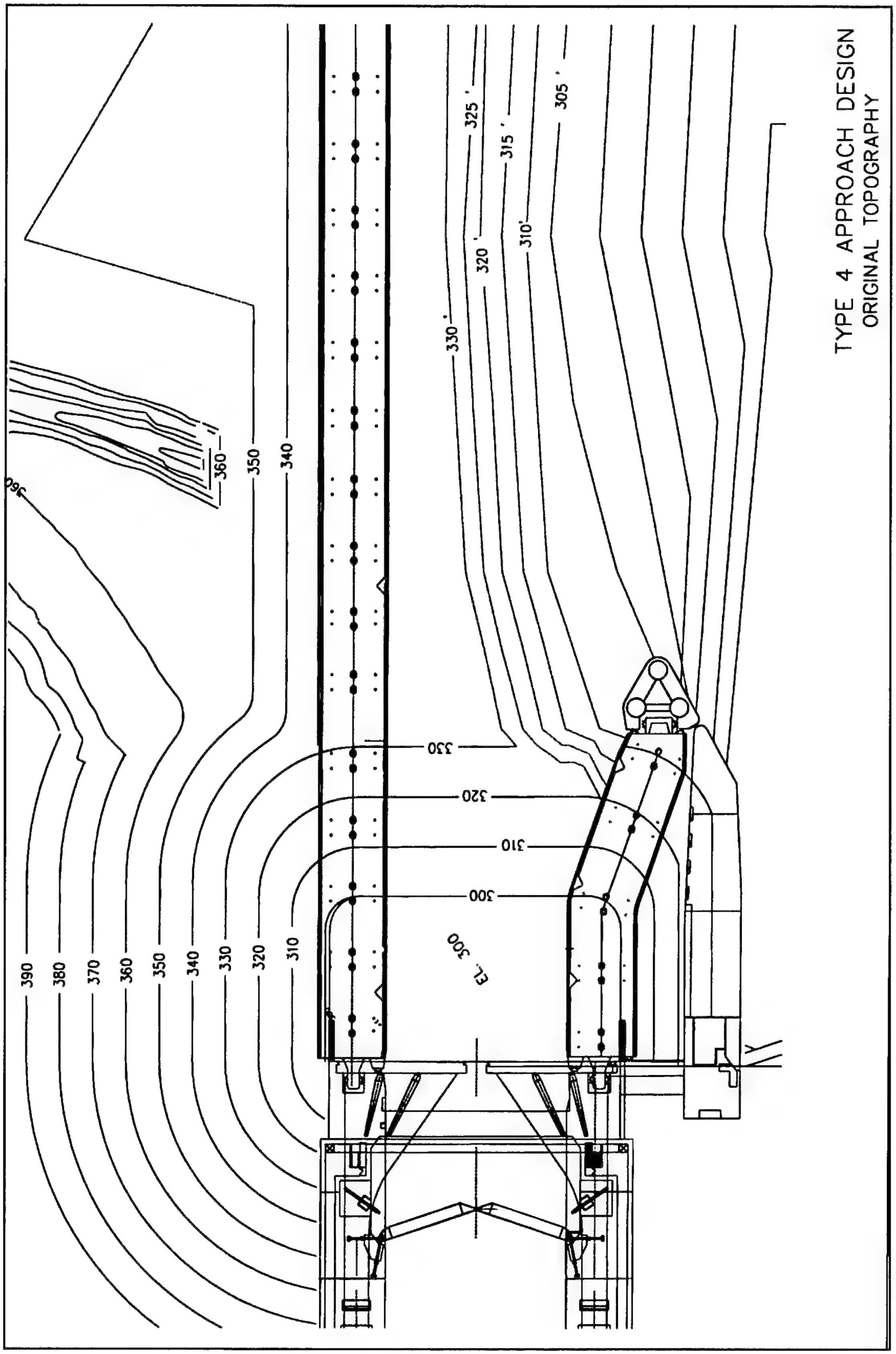
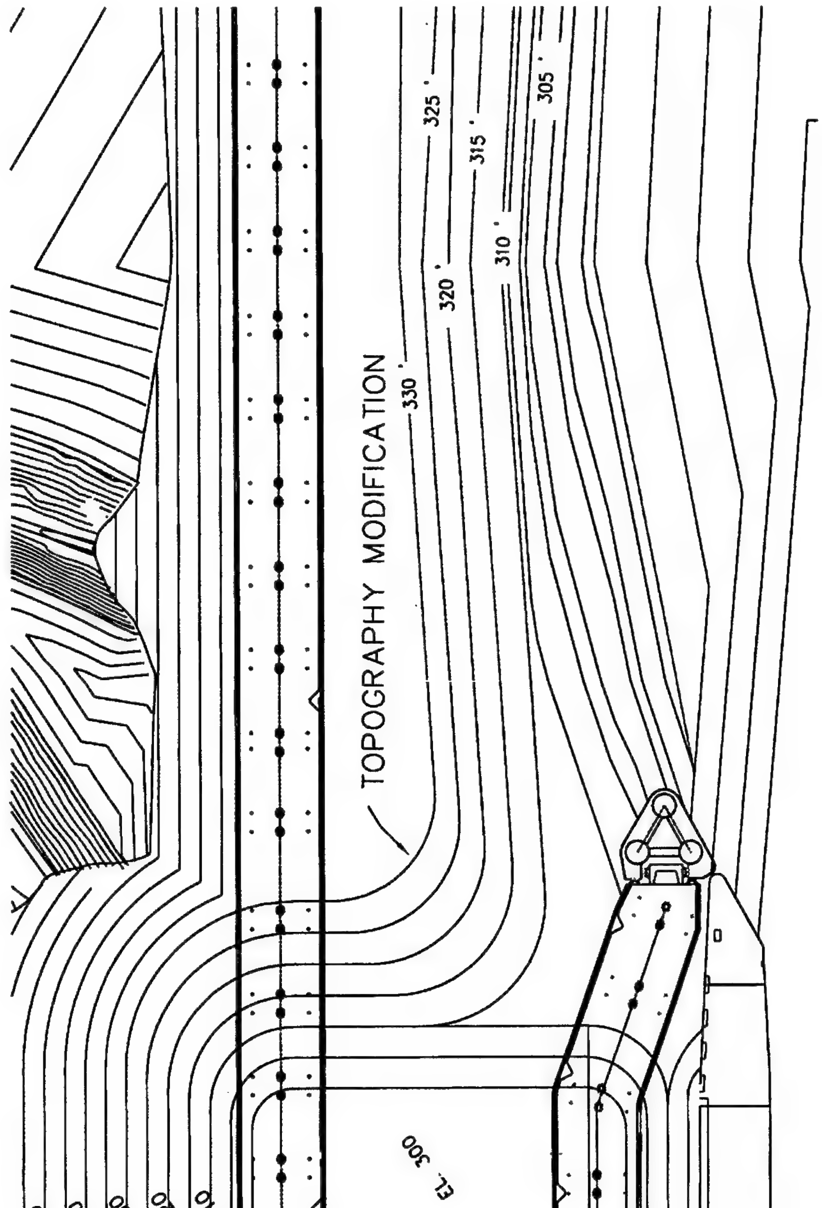
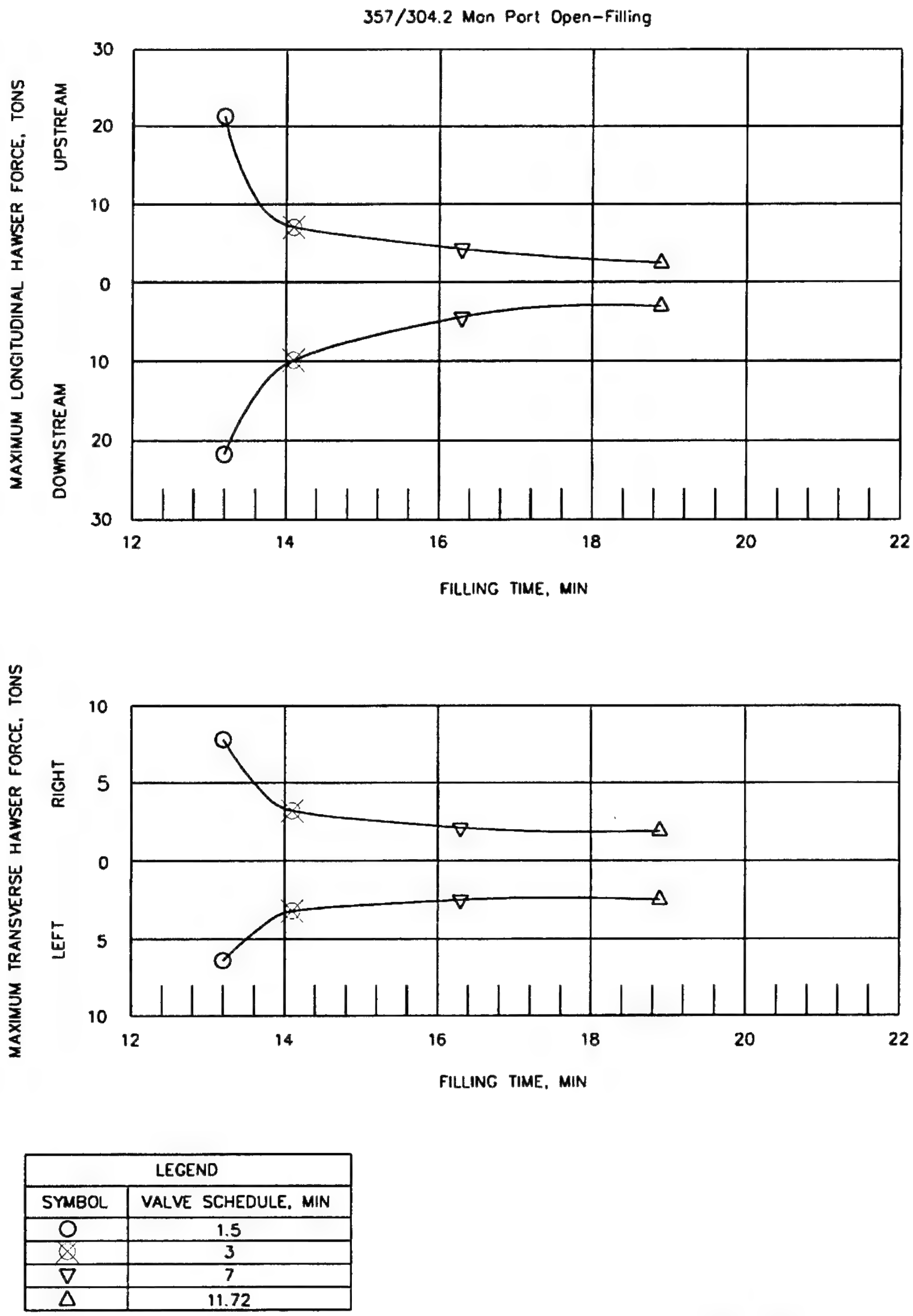

TYPE 4 APPROACH DESIGN
ORIGINAL TOPOGRAPHY
EL. 300
390
380
370
360
350
340
330
320
310
300
305 '
310'
315 '
320 '
325 '
330 '

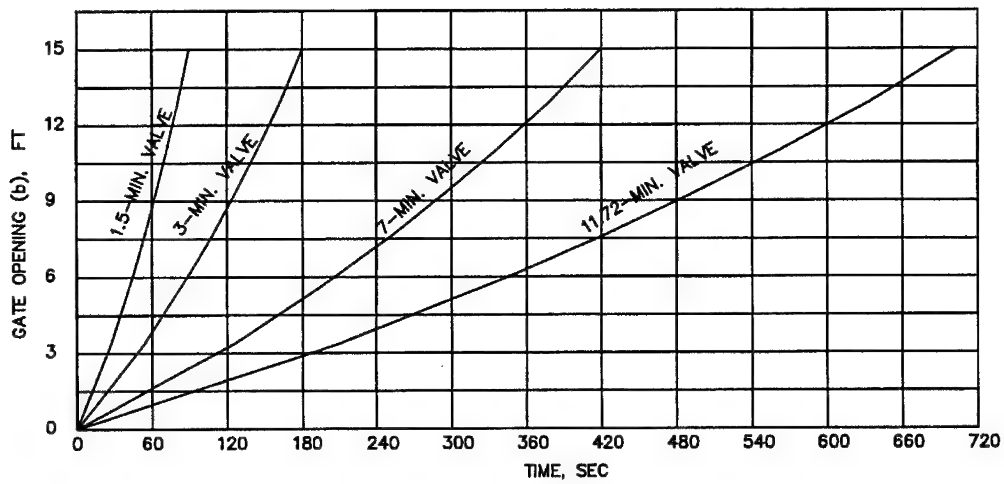
Plate 5



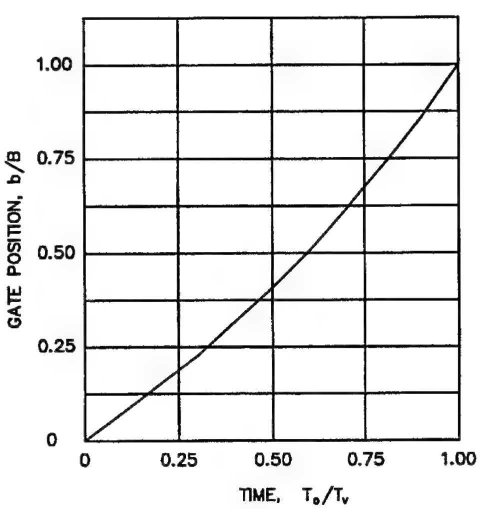
TYPE 5 APPROACH DESIGN
MODIFIED TOPOGRAPHY

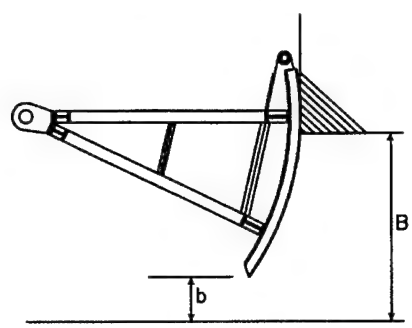


16.154-m (53-ft) LIFT
HAWSER FORCES
DURING FILLING
ORIGINAL DESIGN



b/B	T_o/T_v
0	0
0.075	0.10
0.150	0.20
0.225	0.30
0.317	0.40
0.408	0.50
0.508	0.60
0.617	0.70
0.733	0.80
0.858	0.90
1.000	1.00





REVERSE TAINTER VALVE

T_o = TIME SINCE OPENING BEGAN

T_v = TIME TO OPEN FULL

B = 15 FT (4.57 m)

b = VERTICAL DIST. FROM LIP TO FLOOR

TYPE 1 DESIGN
VALVE OPENING CURVES

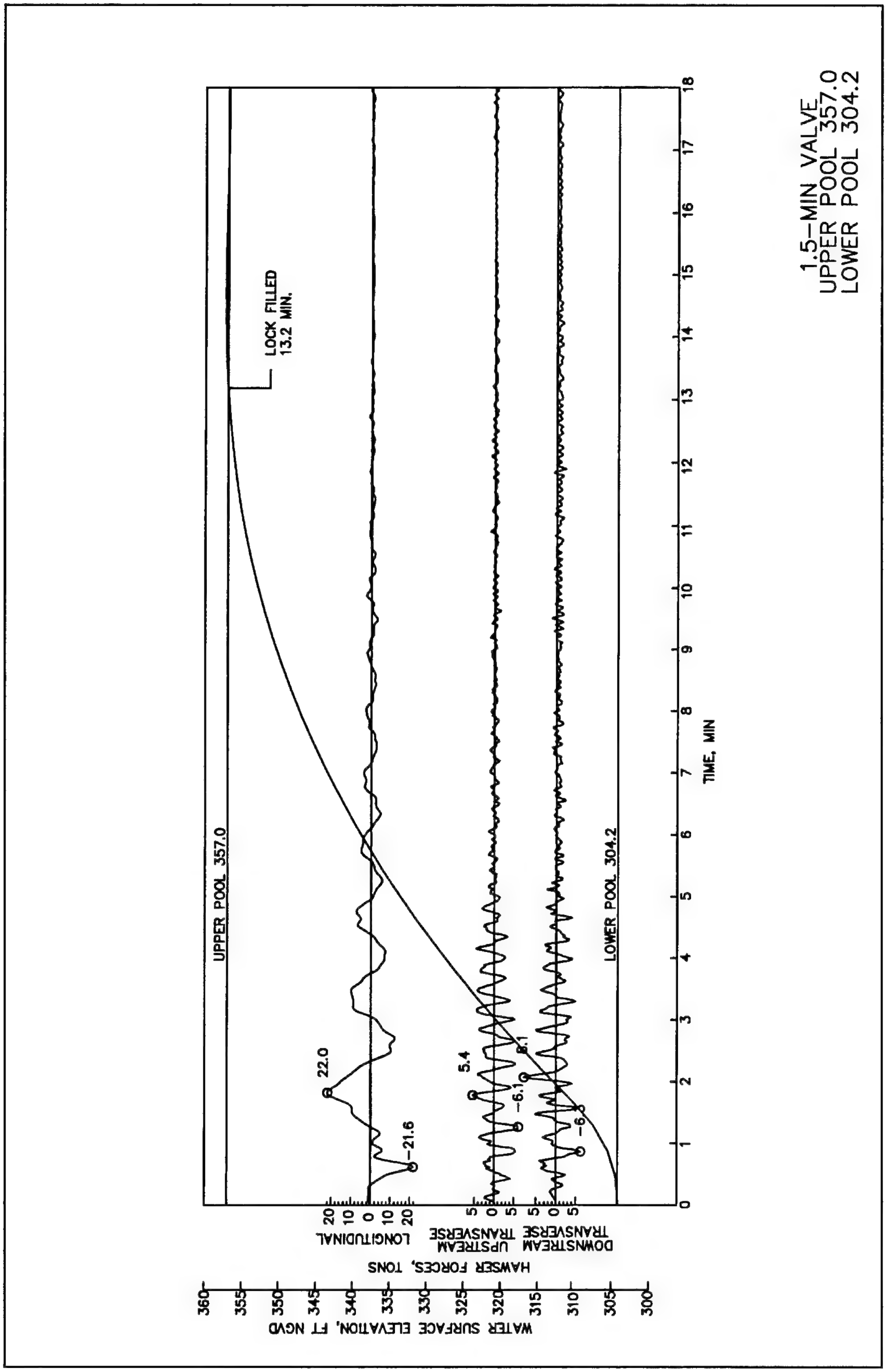
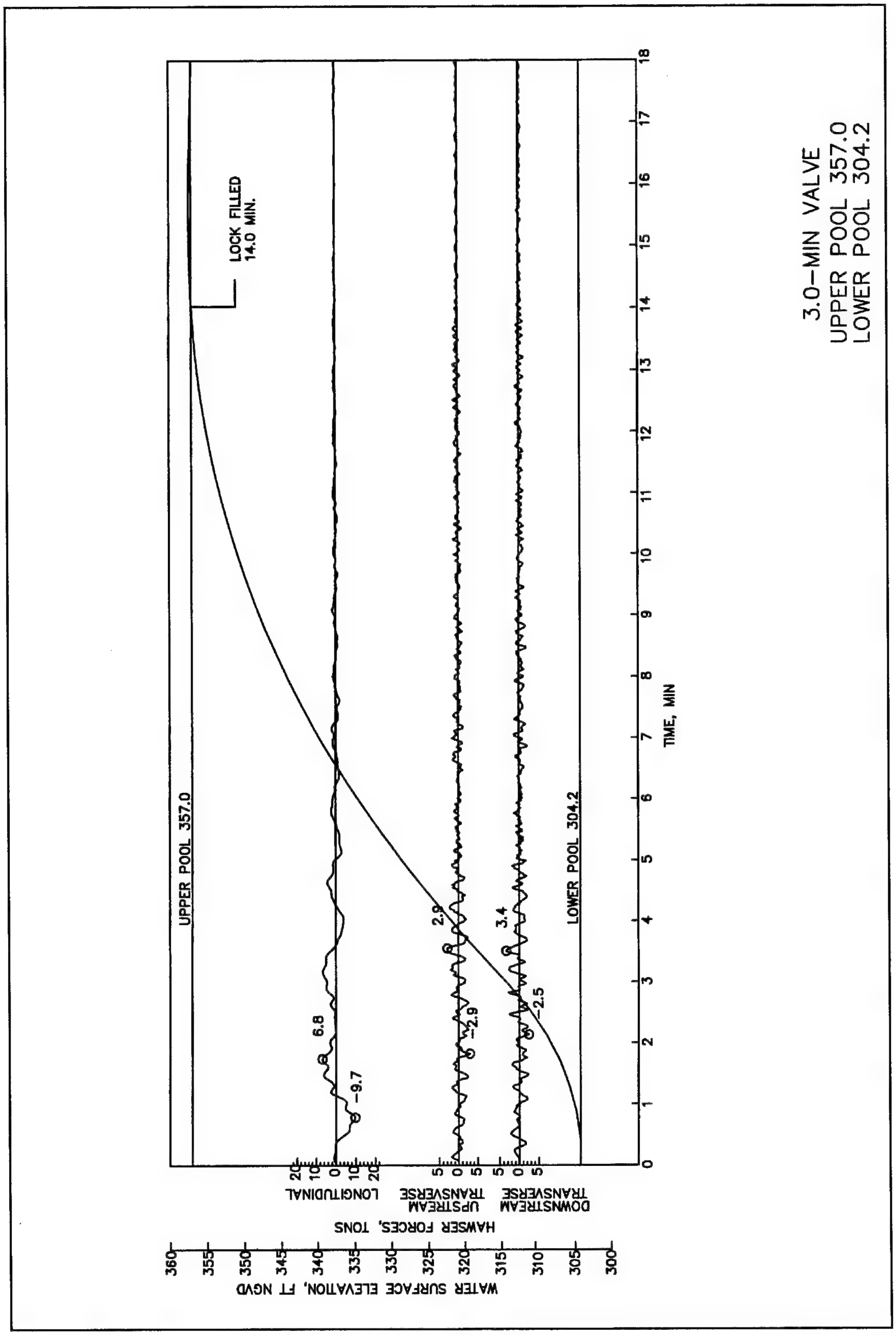
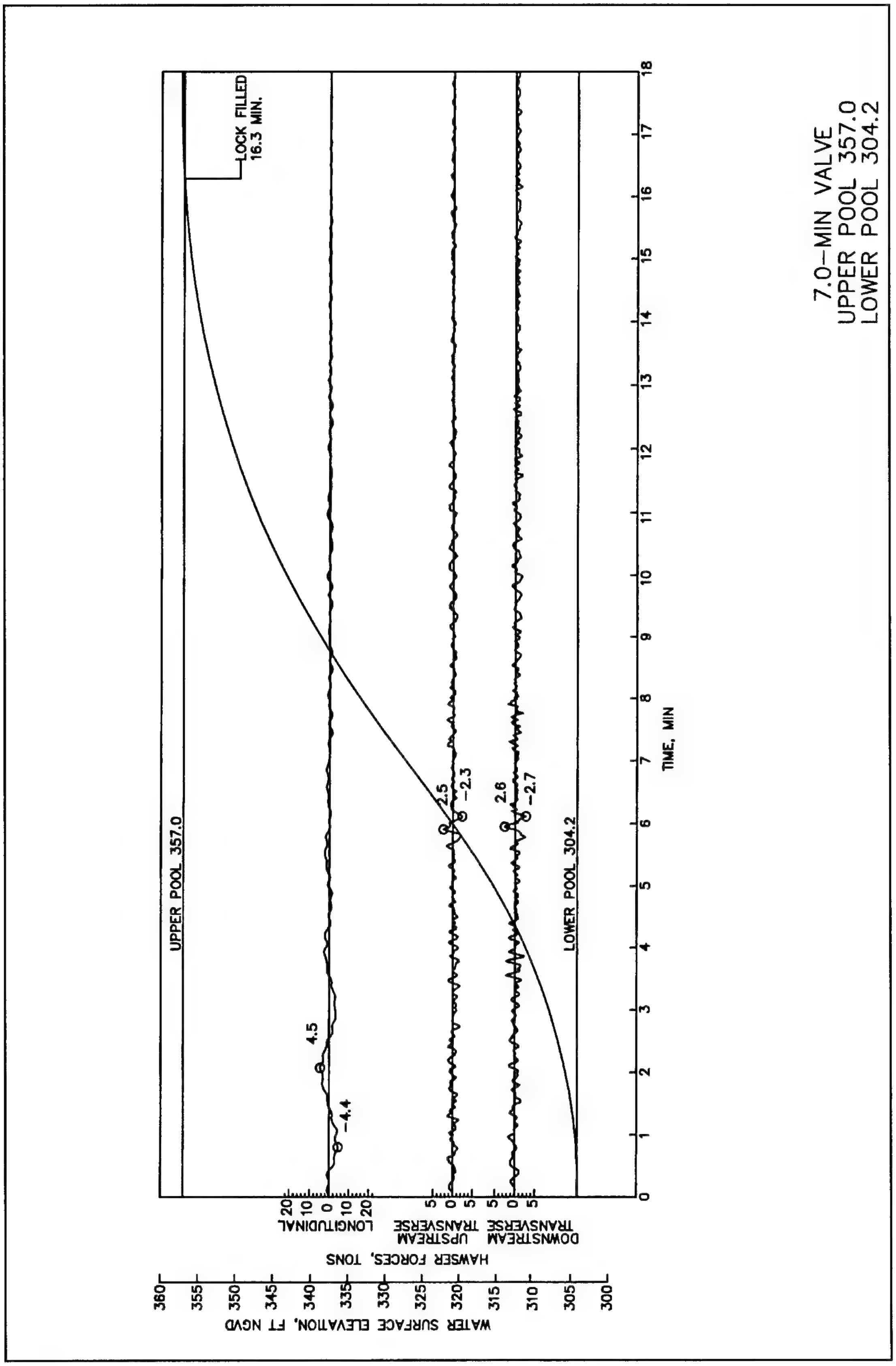

1.5–MIN VALVE
UPPER POOL 357.0
LOWER POOL 304.2
UPPER POOL 357.0
LOWER POOL 304.2
LOCK FILLED
13.2 MIN.
22.0
−21.6
5.4
−6.1
6.1
−6.3
TIME, MIN
WATER SURFACE ELEVATION, FT NGVD
HAWSER FORCES, TONS
LONGITUDINAL
UPSTREAM TRANSVERSE
DOWNSTREAM TRANSVERSE

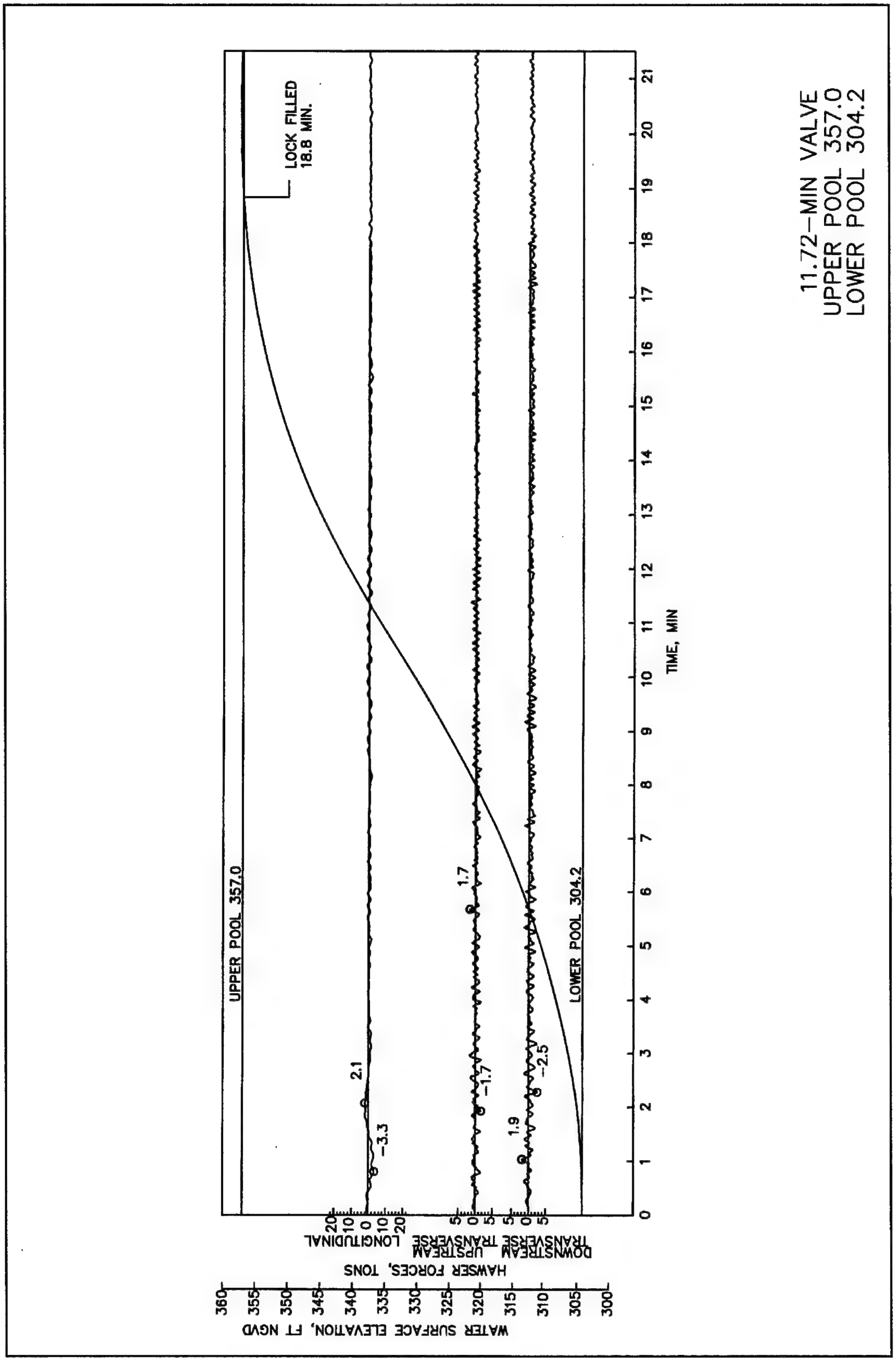
Plate 9

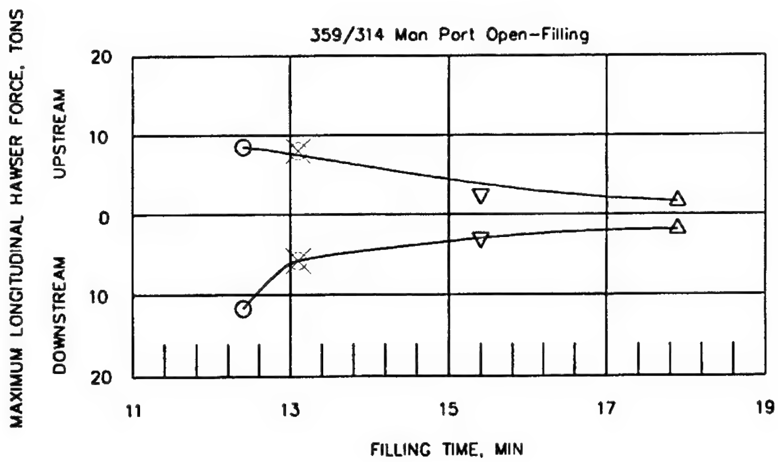


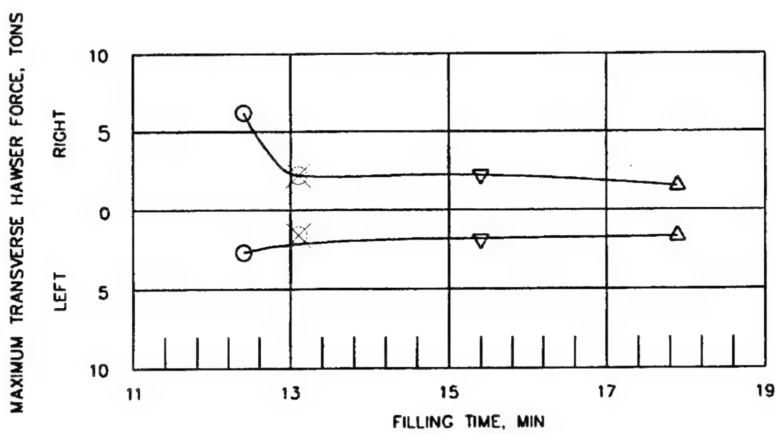
3.0–MIN VALVE
UPPER POOL 357.0
LOWER POOL 304.2
LOCK FILLED
14.0 MIN.
UPPER POOL 357.0
LOWER POOL 304.2
TIME, MIN
WATER SURFACE ELEVATION, FT NGVD
HAWSER FORCES, TONS
LONGITUDINAL
UPSTREAM TRANSVERSE
DOWNSTREAM TRANSVERSE
6.8
−9.7
2.9
−2.9
3.4
−2.5



7.0-MIN VALVE
UPPER POOL 357.0
LOWER POOL 304.2
UPPER POOL 357.0
LOWER POOL 304.2
LOCK FILLED
16.3 MIN.
4.5
-4.4
2.5
-2.3
2.6
-2.7
TIME, MIN
WATER SURFACE ELEVATION, FT NGVD
HAWSER FORCES, TONS
LONGITUDINAL
UPSTREAM TRANSVERSE
DOWNSTREAM TRANSVERSE

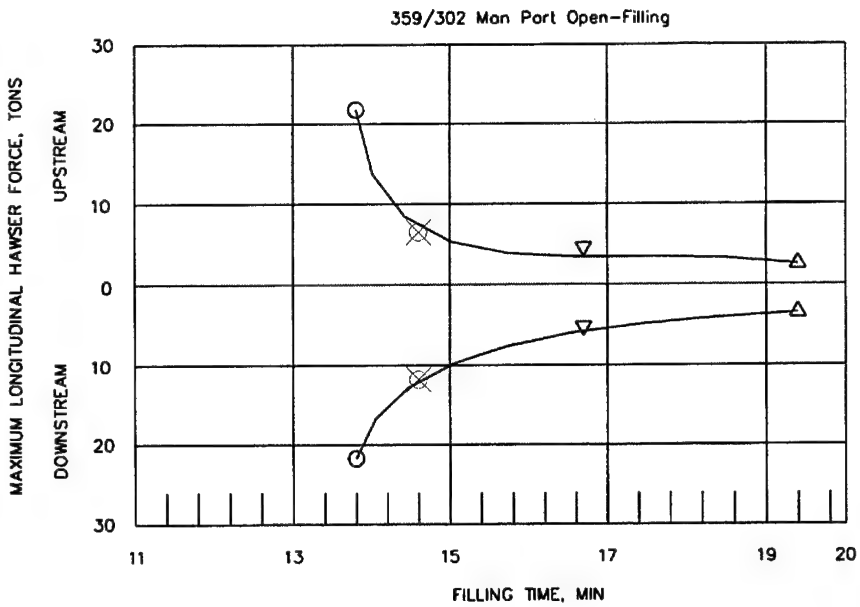

11.72–MIN VALVE
UPPER POOL 357.0
LOWER POOL 304.2
LOCK FILLED 18.8 MIN.
UPPER POOL 357.0
LOWER POOL 304.2
TIME, MIN
WATER SURFACE ELEVATION, FT NGVD
HAWSER FORCES, TONS
LONGITUDINAL
UPSTREAM TRANSVERSE
DOWNSTREAM TRANSVERSE
2.1
–3.3
1.7
–1.7
1.9
–2.5

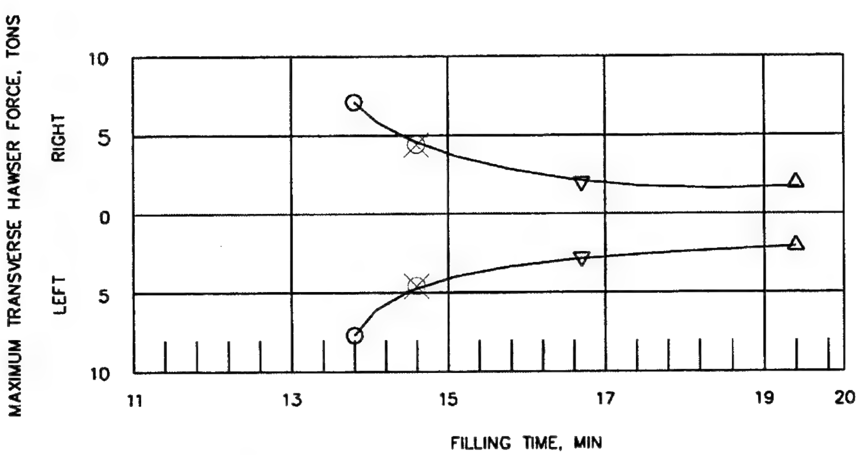




LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
O	1.5
☒	3
▽	7
△	11.72

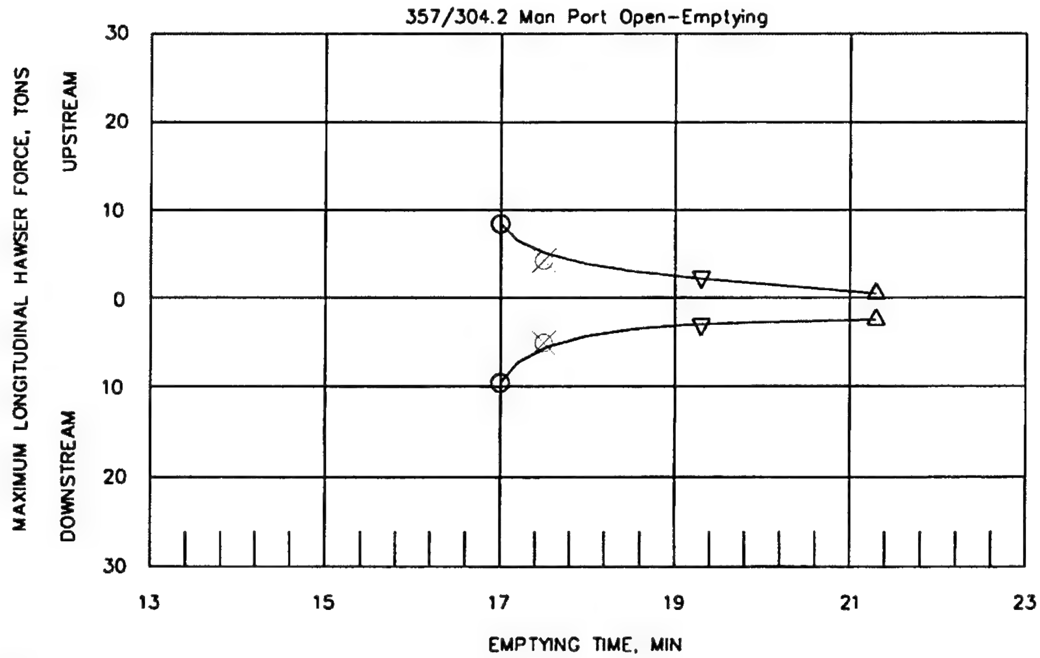
13.716-m (45-ft) LIFT
HAWSER FORCES
DURING FILLING
ORIGINAL DESIGN

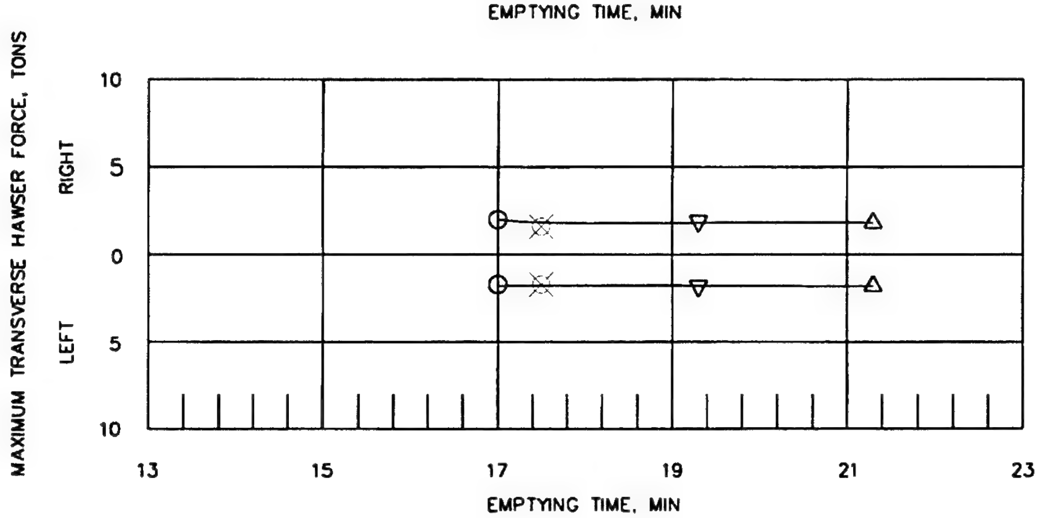




LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

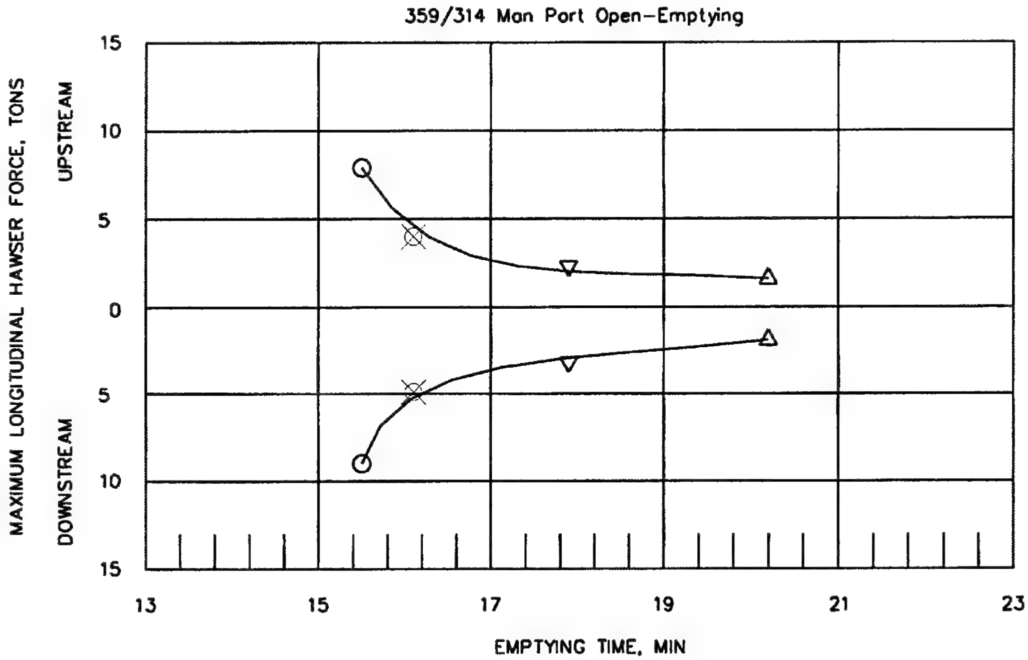
17.373-m (57-ft) LIFT
HAWSER FORCES
DURING FILLING
ORIGINAL DESIGN

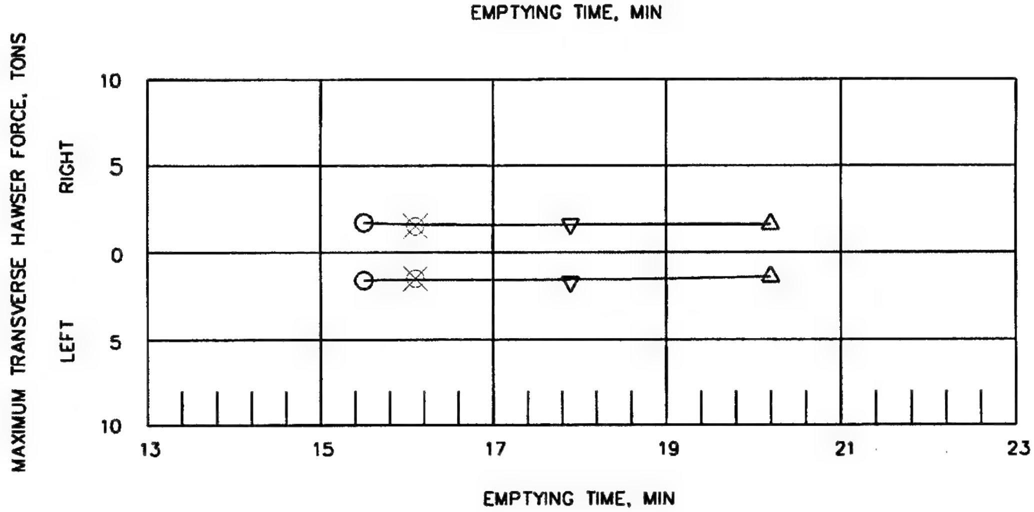




LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

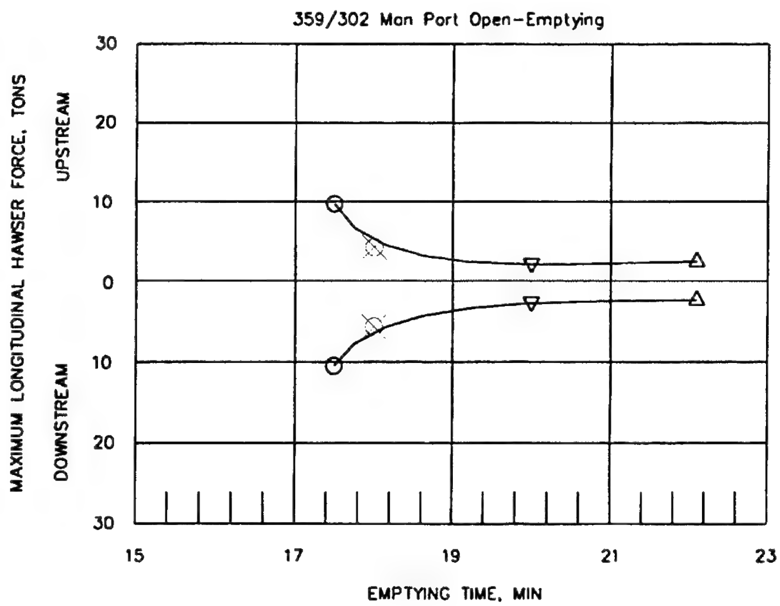
16.154-m (53-ft) LIFT
HAWSER FORCES
DURING EMPTYING
ORIGINAL DESIGN

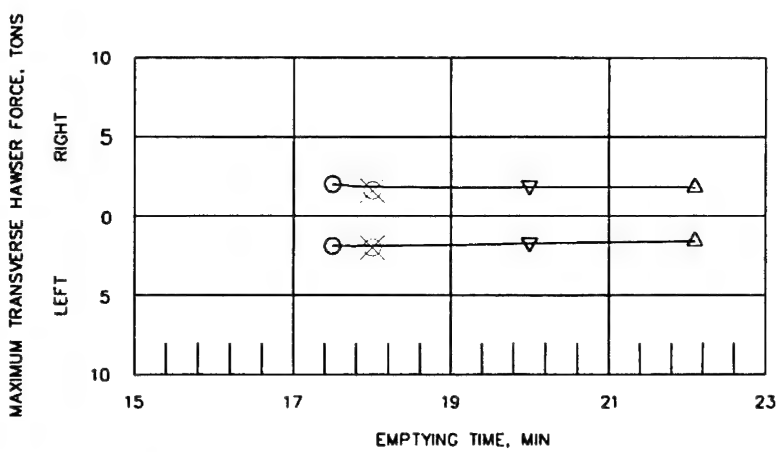




LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

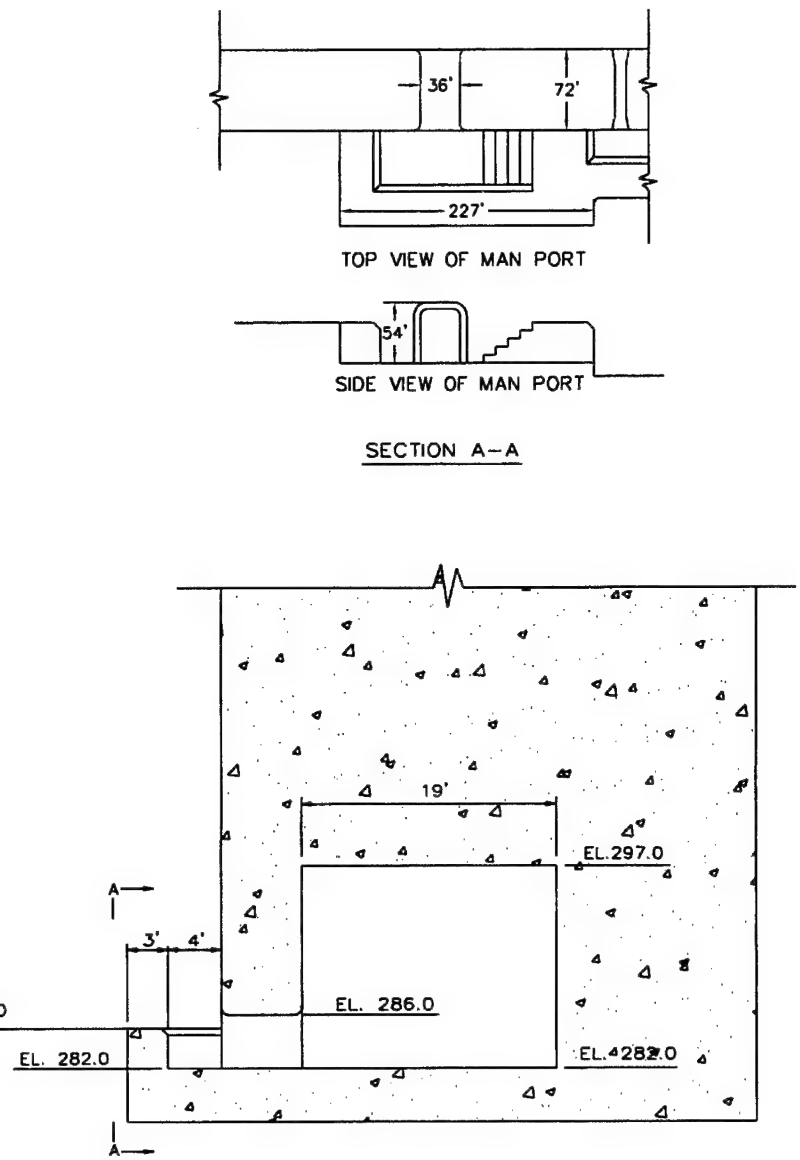
13.716-m (45-ft) LIFT
HAWSER FORCES
DURING EMPTYING
ORIGINAL DESIGN



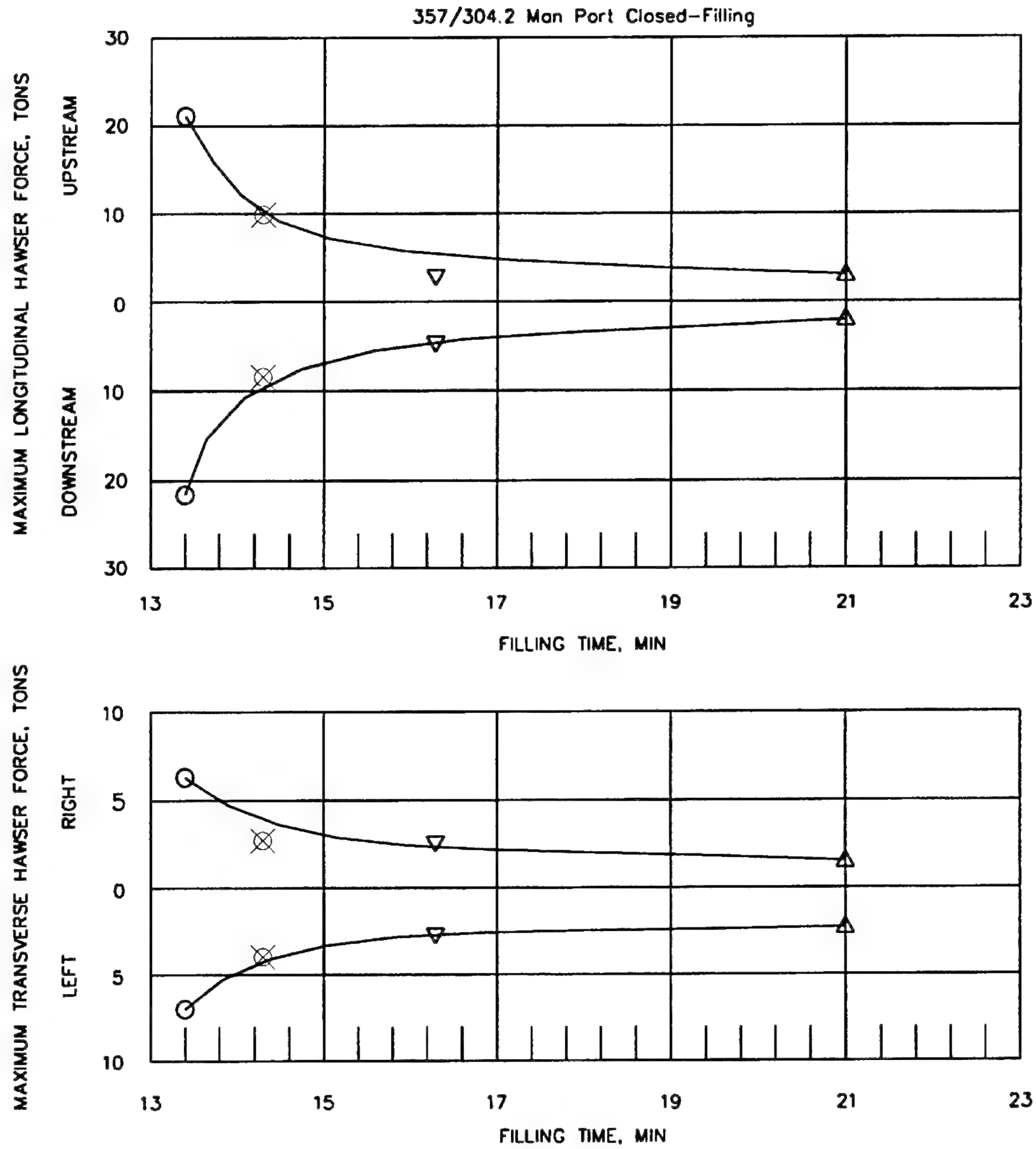


LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

17.373-m (57-ft) LIFT
HAWSER FORCES
DURING EMPTYING
ORIGINAL DESIGN

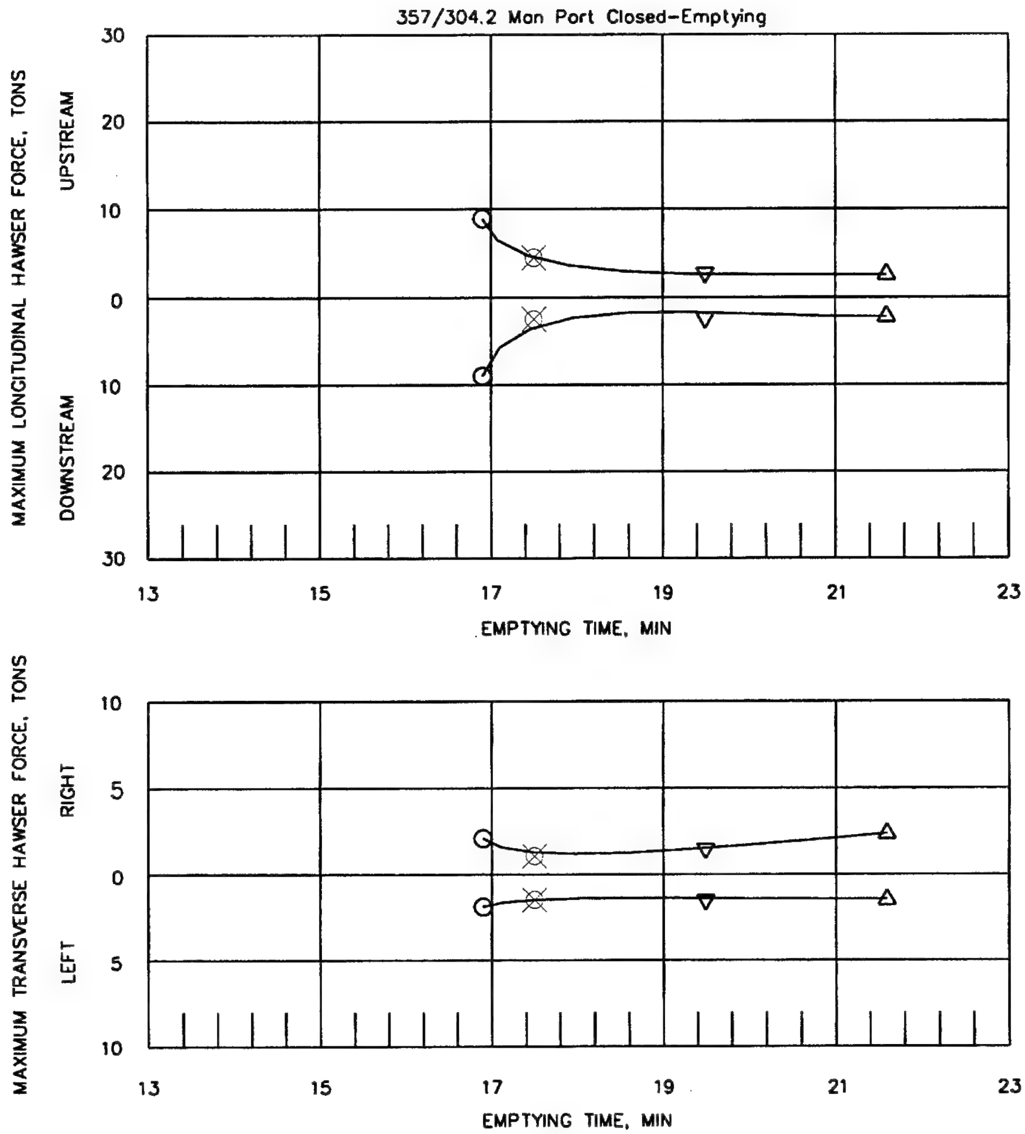


TYPE 1 DESIGN (ORIGINAL)
HUMAN ACCESS PORT



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

16.154-m (53-ft) LIFT
HAWSER FORCES
DURING FILLING
TYPE 2 CHAMBER DESIGN

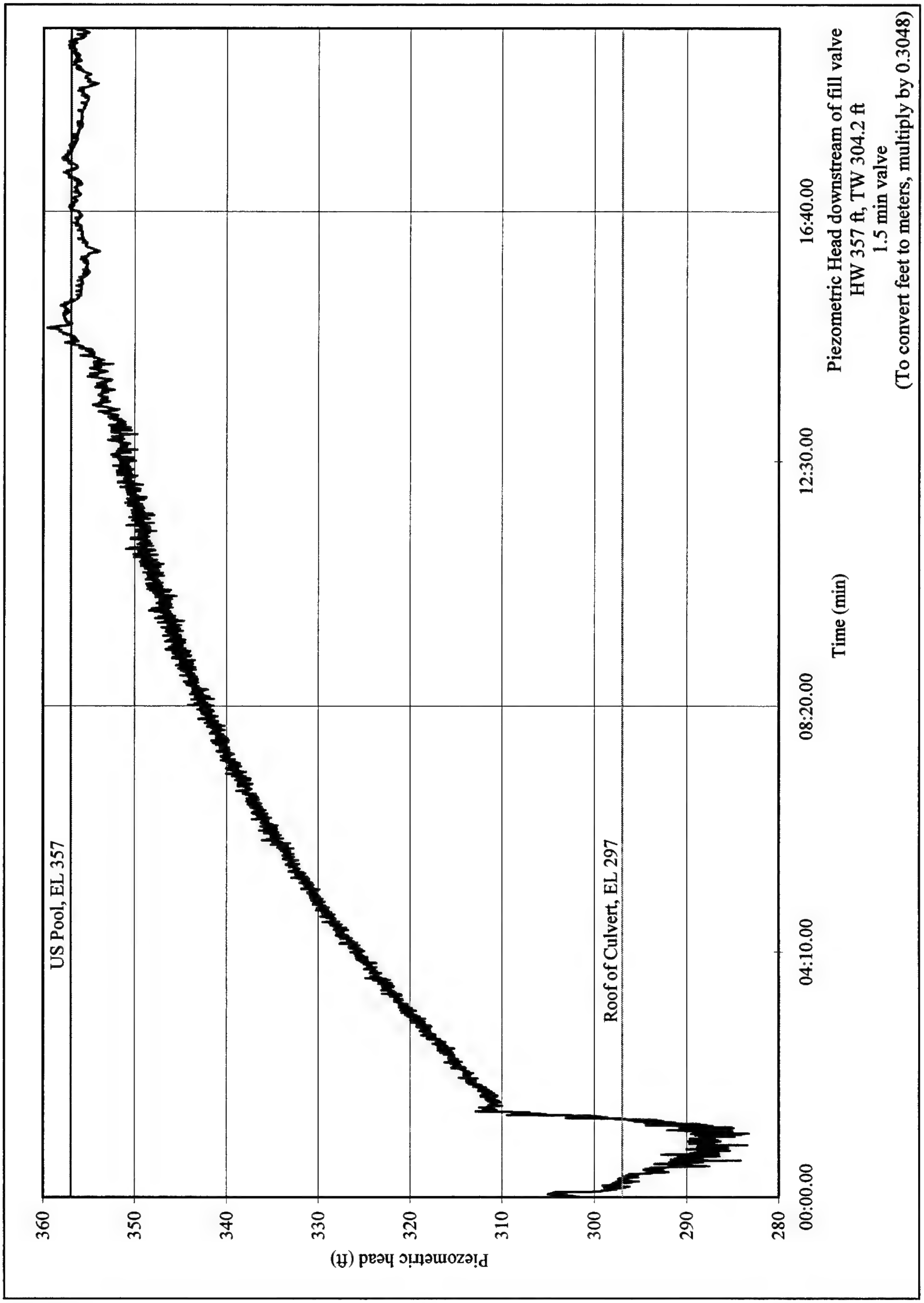


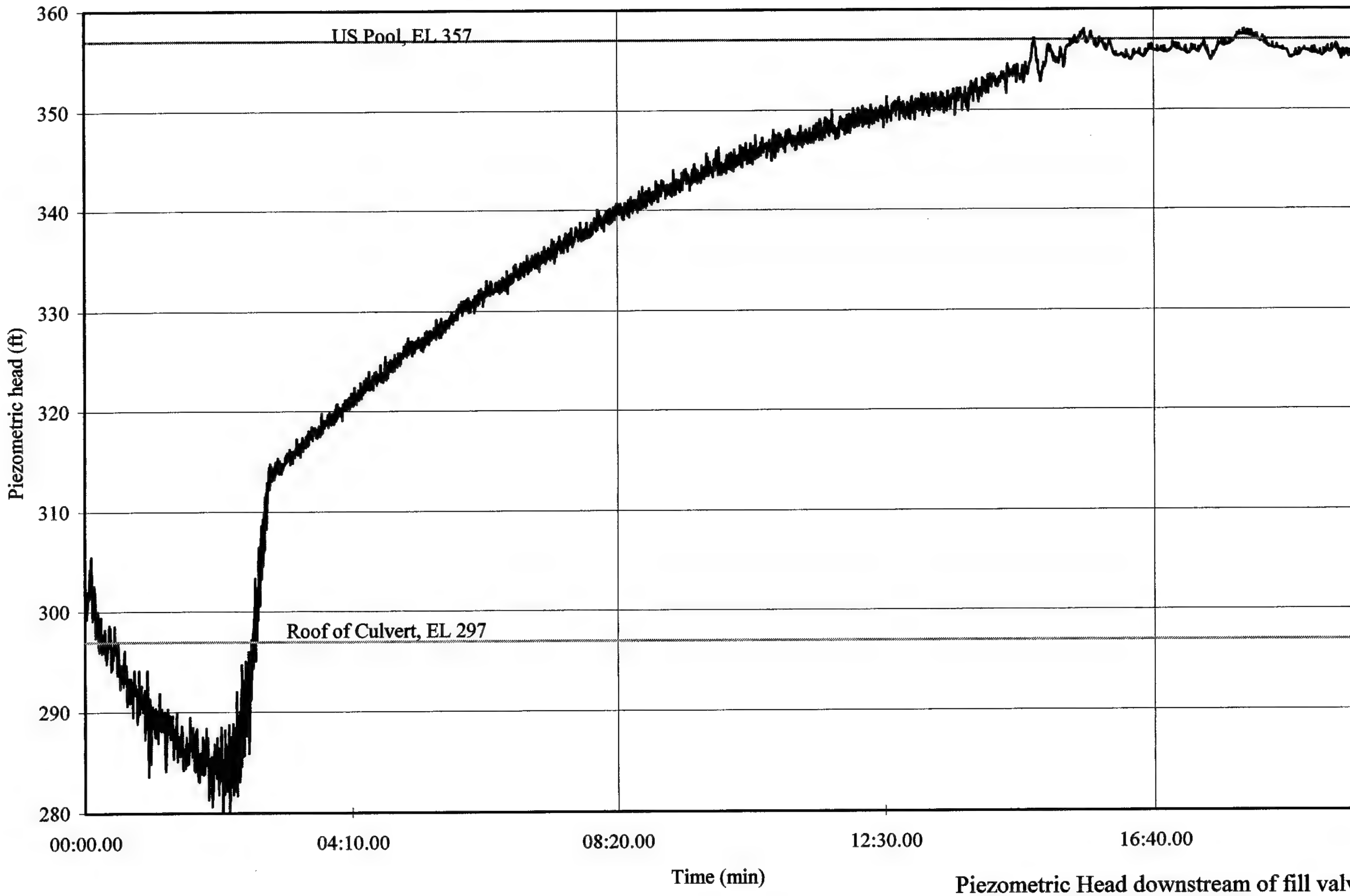
LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	1.5
⊗	3
▽	7
△	11.72

16.154-m (53-ft) LIFT

HAWSER FORCES DURING EMPTYING

TYPE 2 CHAMBER DESIGN


US Pool, EL 357
Roof of Culvert, EL 297
Piezometric head (ft)
360
350
340
330
320
310
300
290
280
00:00.00
04:10.00
08:20.00
12:30.00
16:40.00
Time (min)
Piezometric Head downstream of fill valve
HW 357 ft, TW 304.2 ft
1.5 min valve
(To convert feet to meters, multiply by 0.3048)



Piezometric Head downstream of fill valve
HW 357 ft, TW 304.2 ft
3.0 min valve

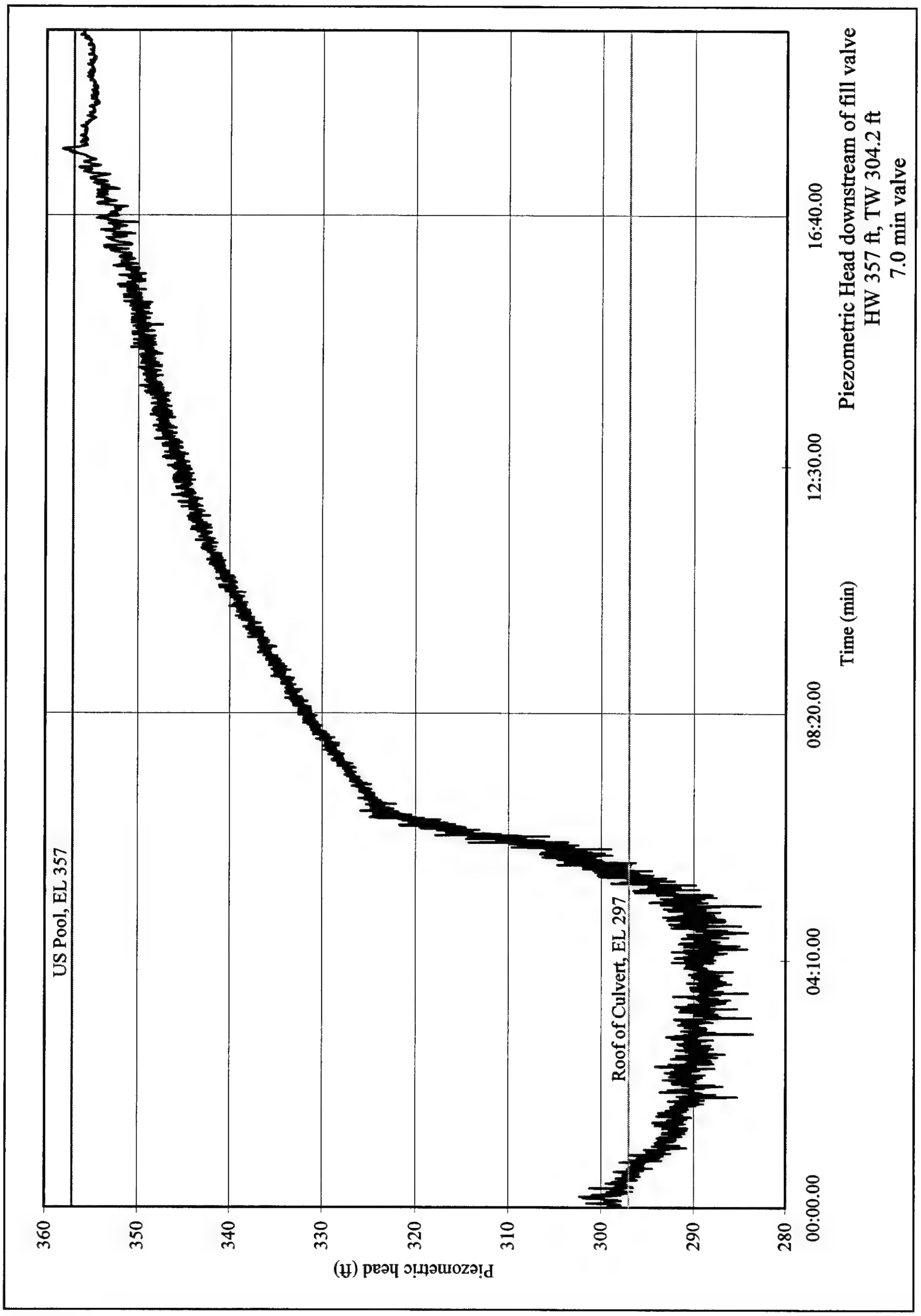
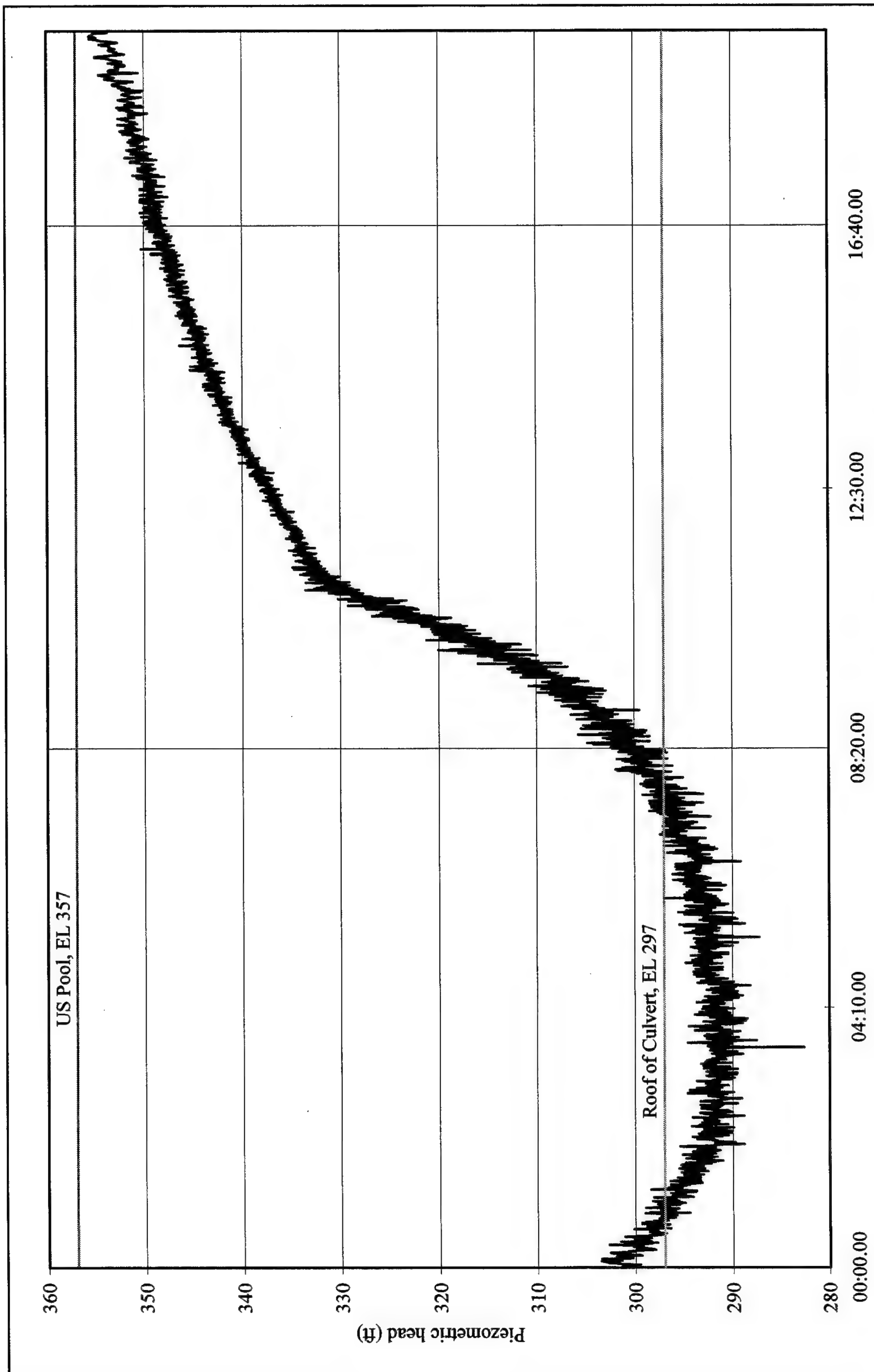
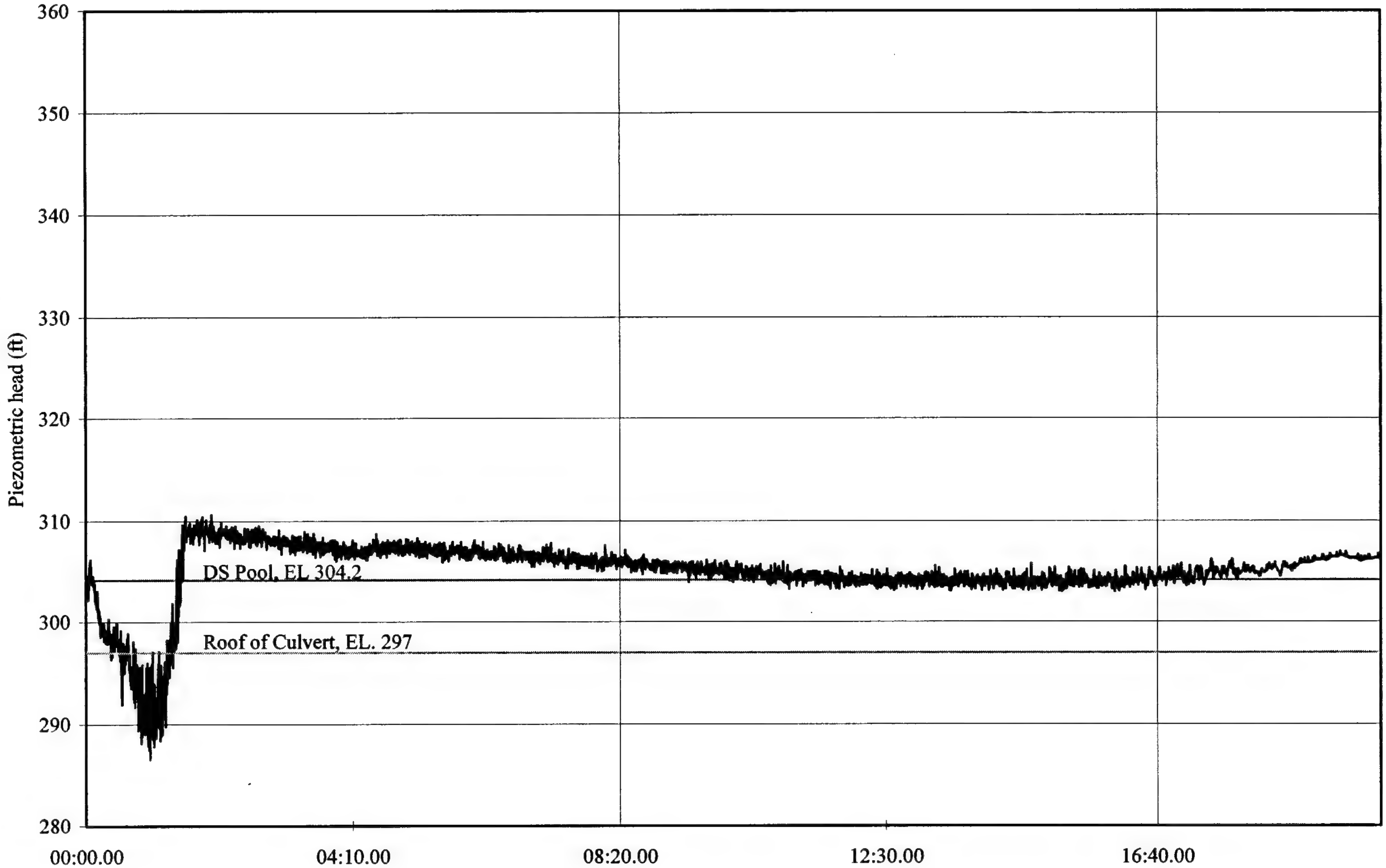

Piezometric Head downstream of fill valve
HW 357 ft, TW 304.2 ft
7.0 min valve
US Pool, EL 357
Roof of Culvert, EL 297
Piezometric head (ft)
Time (min)
360
350
340
330
320
310
300
290
280
00:00.00
04:10.00
08:20.00
12:30.00
16:40.00

Plate 23



Piezometric Head downstream of fill valve
HW 357 ft, TW 304.2 ft
11.72 min valve



Piezometric Head downstream of empty valve
HW 357 ft, TW 304.2 ft
1.5 min valve

Plate 25

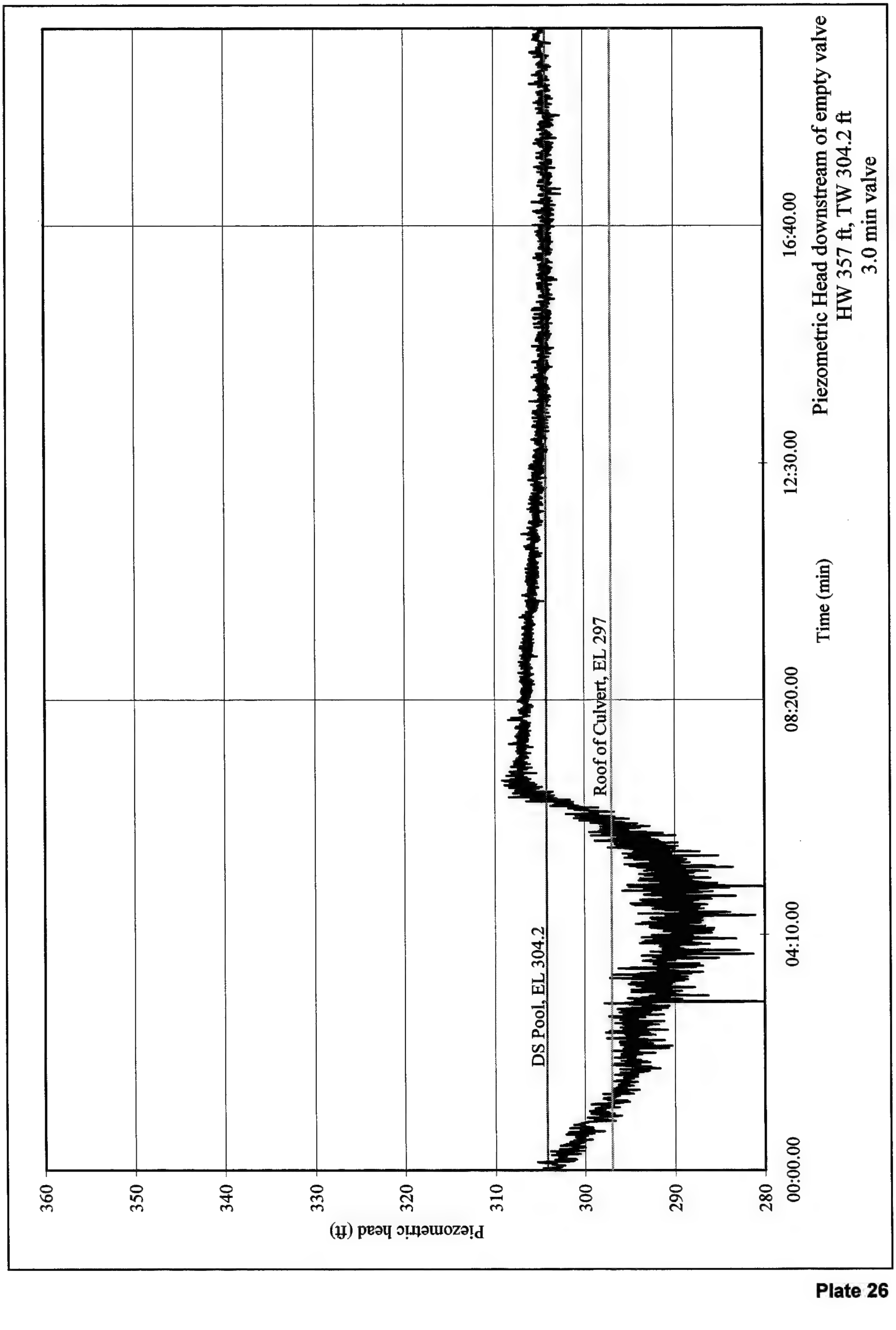
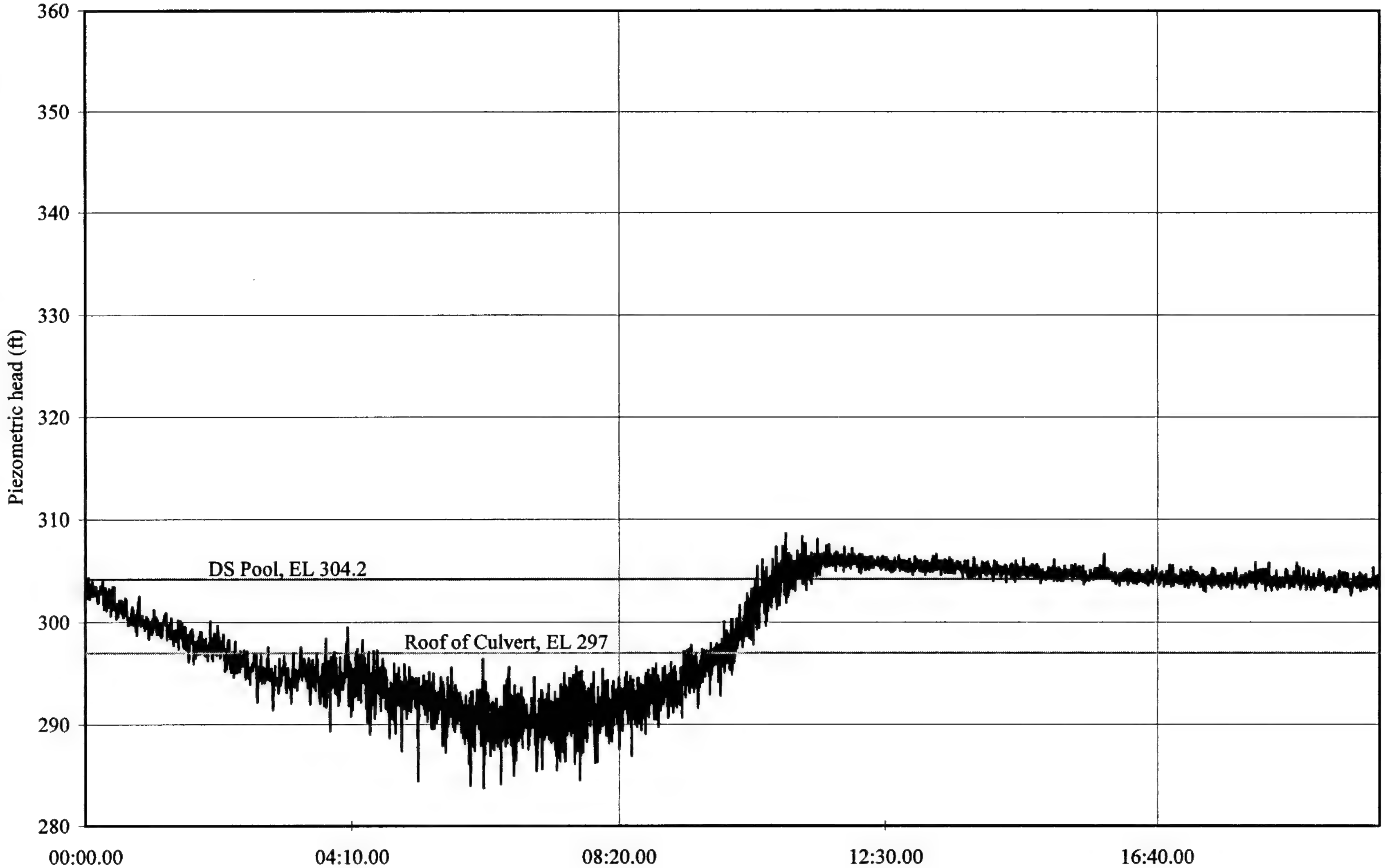
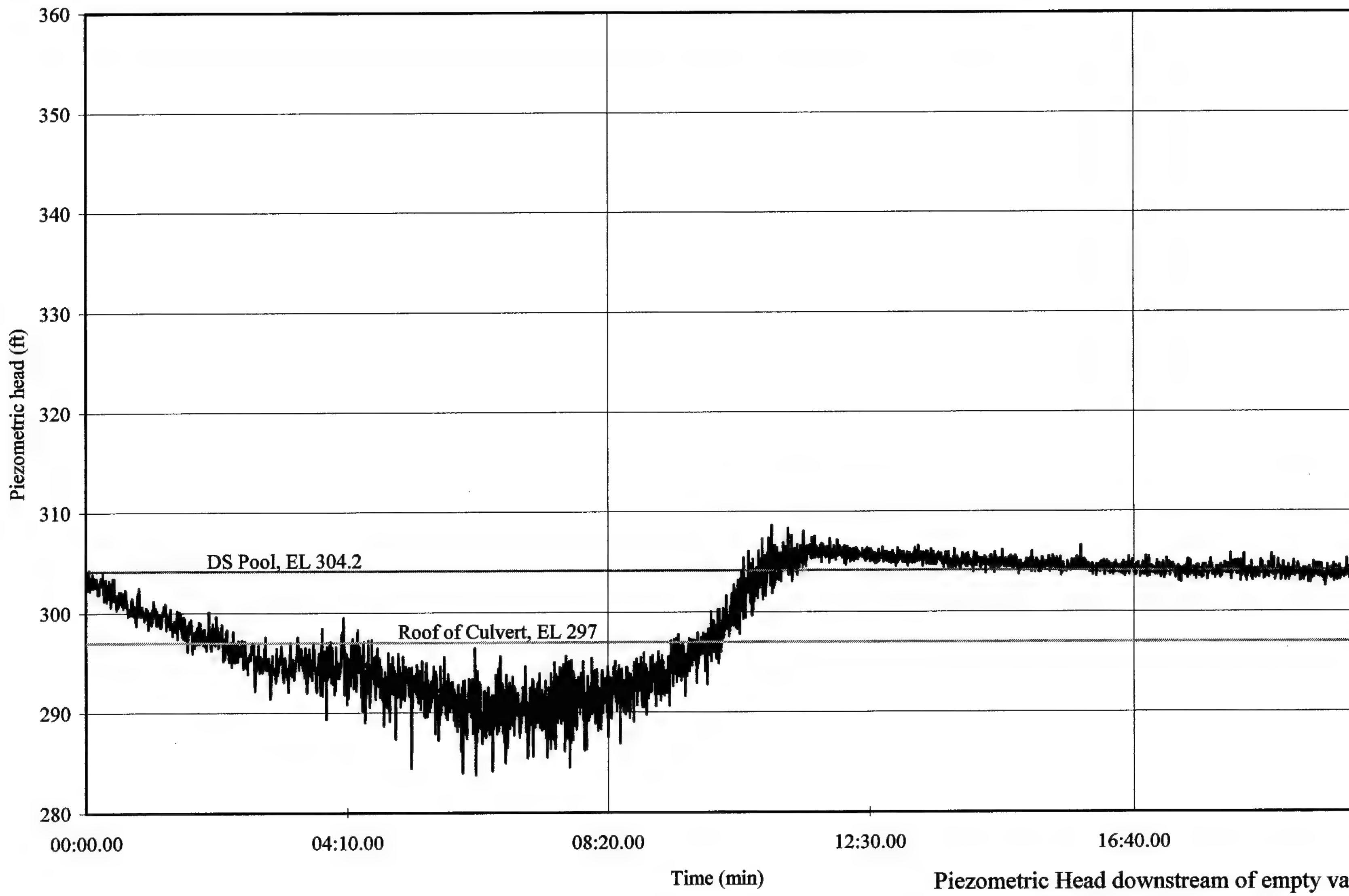

Piezometric Head downstream of empty valve
HW 357 ft, TW 304.2 ft
3.0 min valve
Piezometric head (ft)
Time (min)
DS Pool, EL 304.2
Roof of Culvert, EL 297
360
350
340
330
320
310
300
290
280
00:00.00
04:10.00
08:20.00
12:30.00
16:40.00

Plate 26



Piezometric Head downstream of empty valve
HW 357 ft, TW 304.2 ft
7.0 min valve



Piezometric Head downstream of empty valve
HW 357 ft, TW 304.2 ft
11.72 min valve

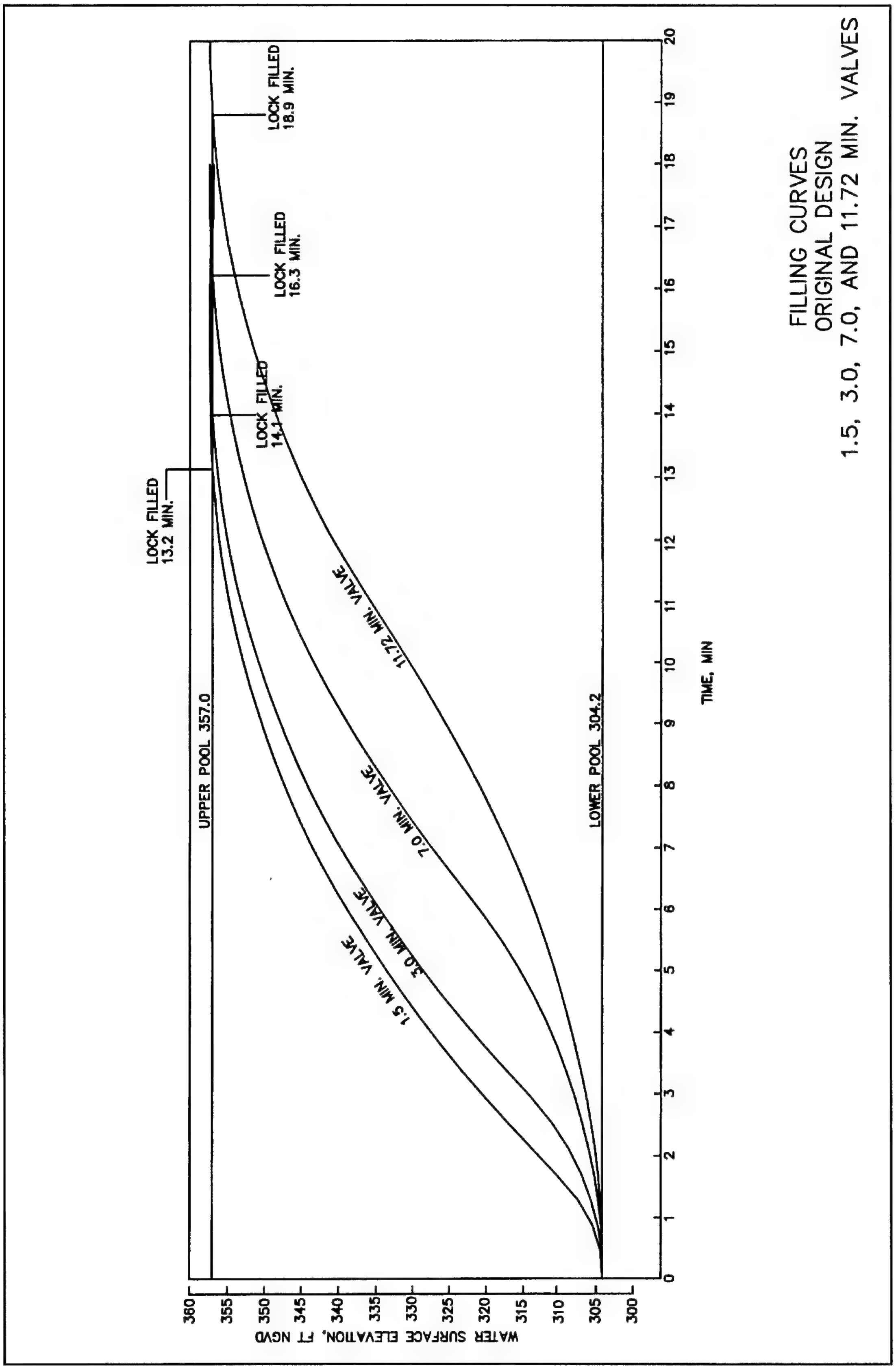
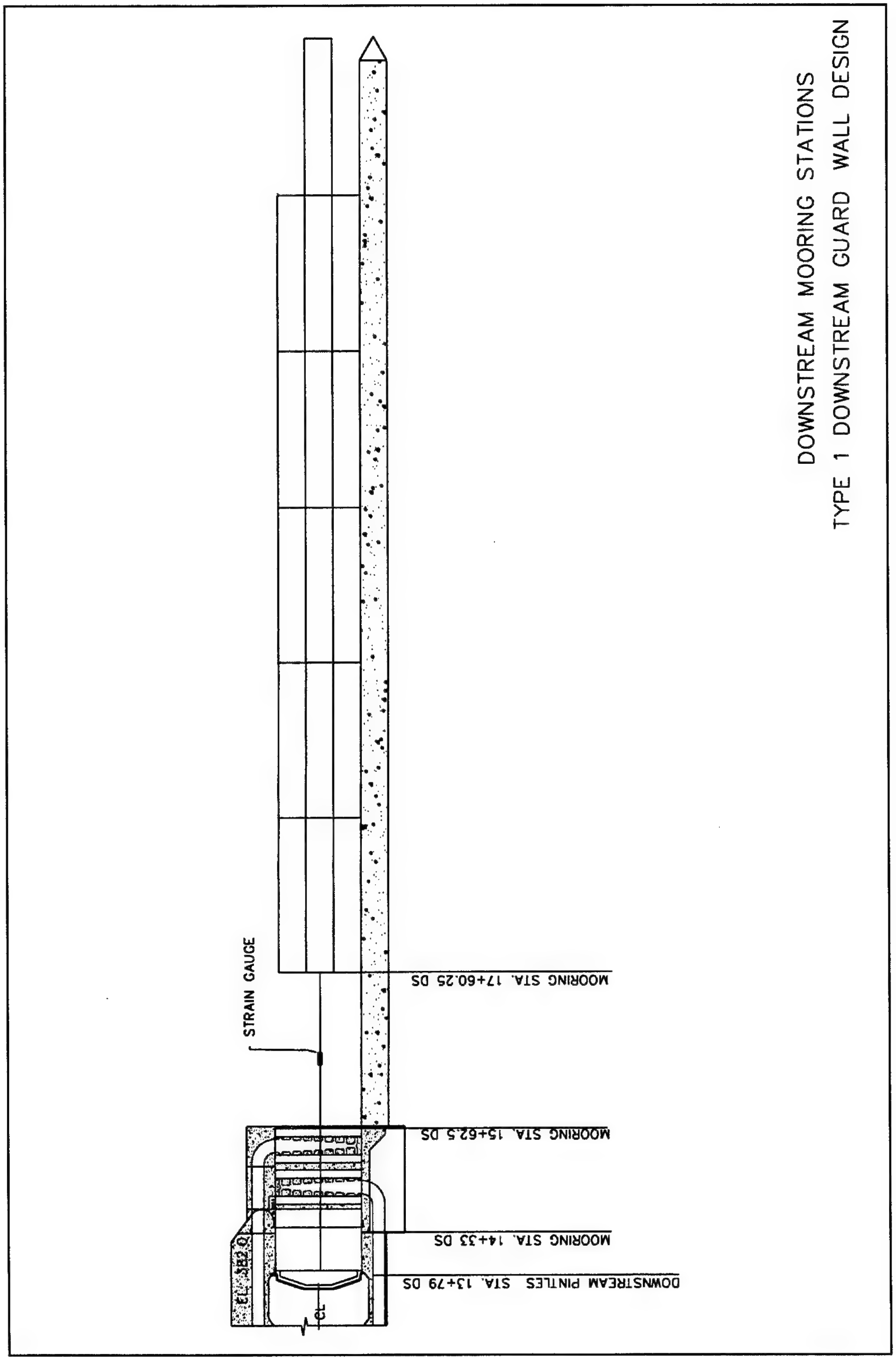
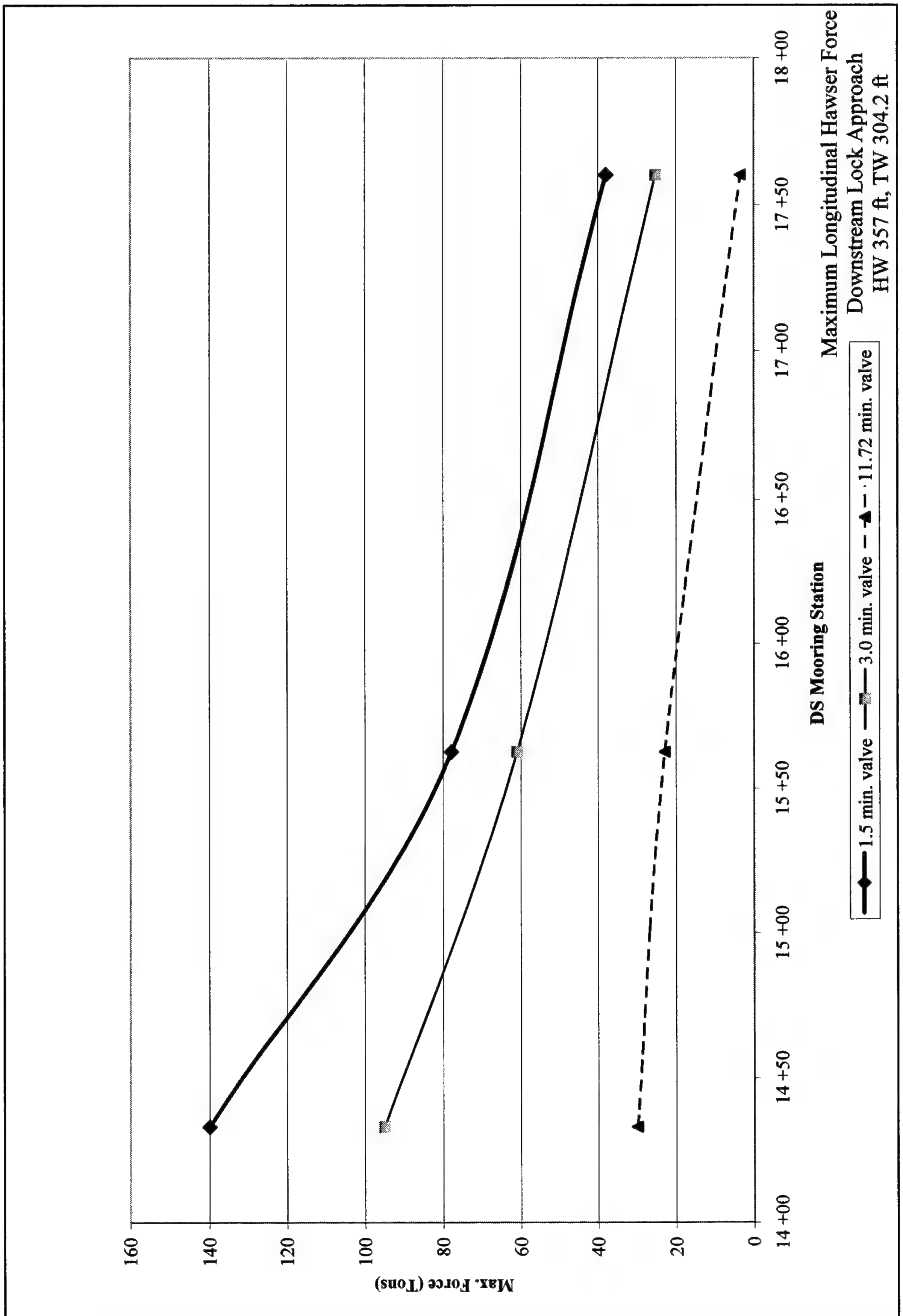

FILLING CURVES
ORIGINAL DESIGN
1.5, 3.0, 7.0, AND 11.72 MIN. VALVES
WATER SURFACE ELEVATION, FT NGVD
TIME, MIN
UPPER POOL 357.0
LOWER POOL 304.2
LOCK FILLED 13.2 MIN.
LOCK FILLED 14.1 MIN.
LOCK FILLED 16.3 MIN.
LOCK FILLED 18.9 MIN.
1.5 MIN. VALVE
3.0 MIN. VALVE
7.0 MIN. VALVE
11.72 MIN. VALVE

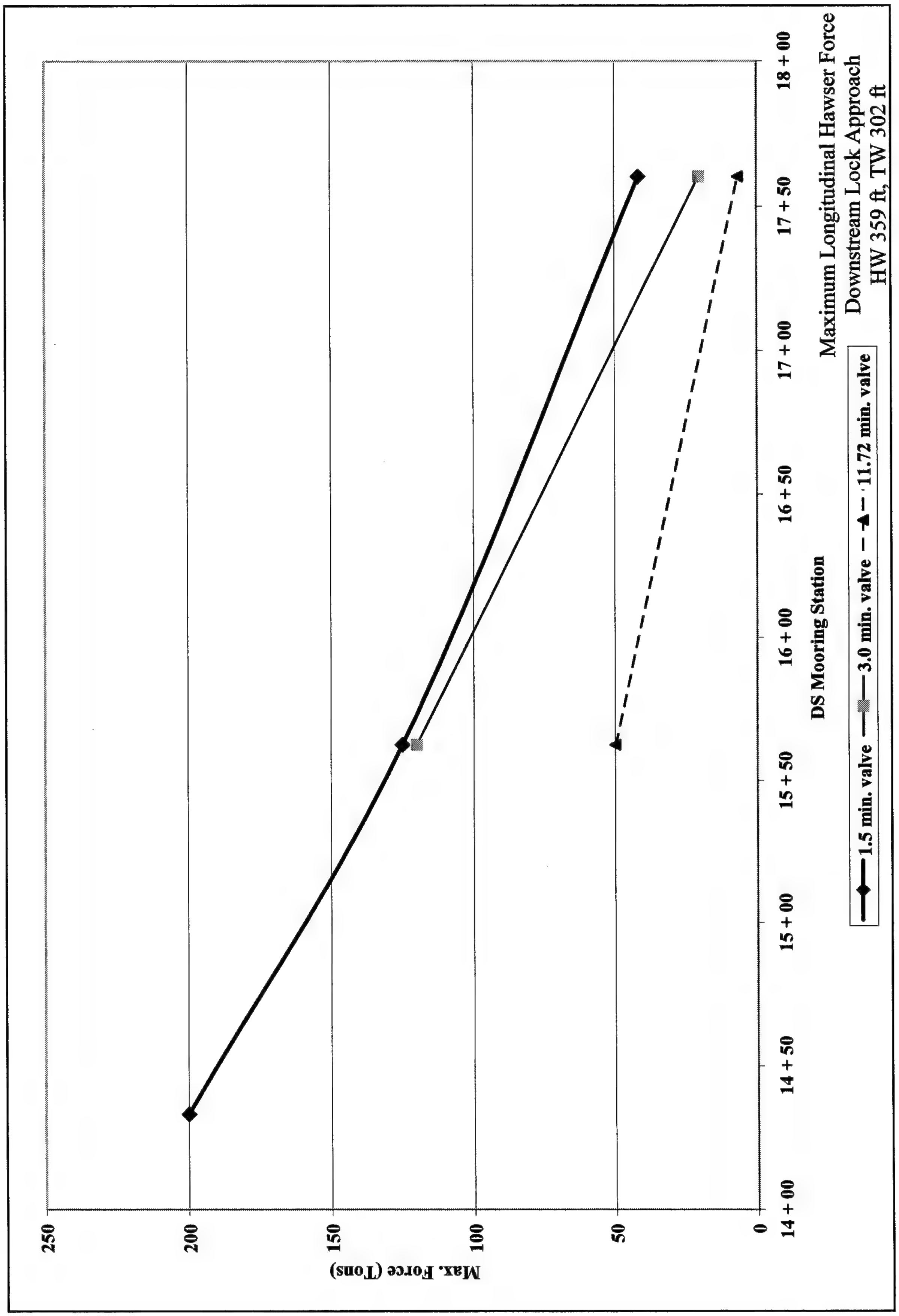
Plate 29



DOWNSTREAM MOORING STATIONS
TYPE 1 DOWNSTREAM GUARD WALL DESIGN



Maximum Longitudinal Hawser Force
Downstream Lock Approach
HW 357 ft, TW 304.2 ft
Max. Force (Tons)
DS Mooring Station
160
140
120
100
80
60
40
20
0
14 +00
14 +50
15 +00
15 +50
16 +00
16 +50
17 +00
17 +50
18 +00
1.5 min. valve
3.0 min. valve
11.72 min. valve


Maximum Longitudinal Hawser Force
Downstream Lock Approach
HW 359 ft, TW 302 ft
Max. Force (Tons)
0
50
100
150
200
250
14 + 00
14 + 50
15 + 00
15 + 50
16 + 00
16 + 50
17 + 00
17 + 50
18 + 00
DS Mooring Station
1.5 min. valve
3.0 min. valve
11.72 min. valve

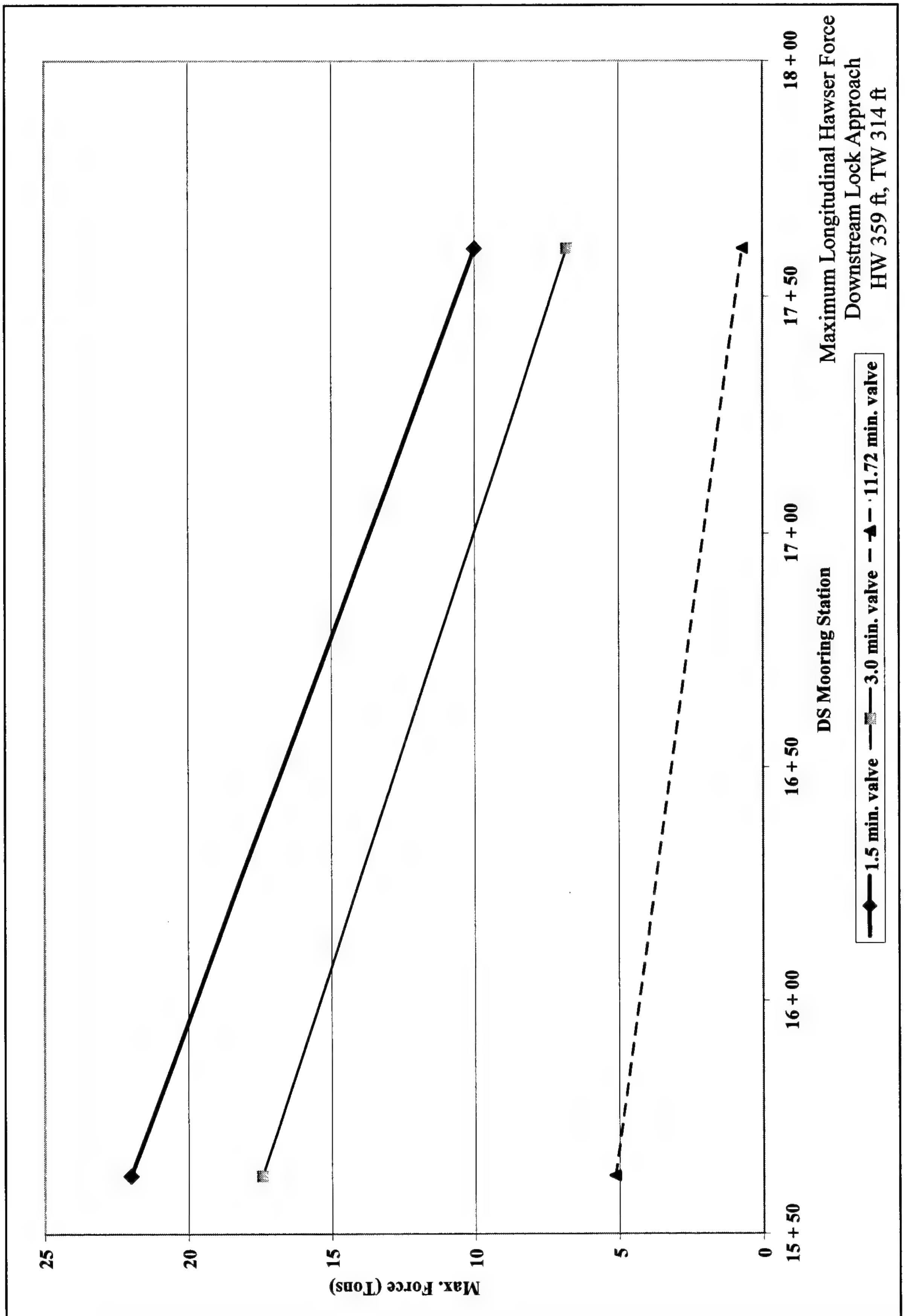
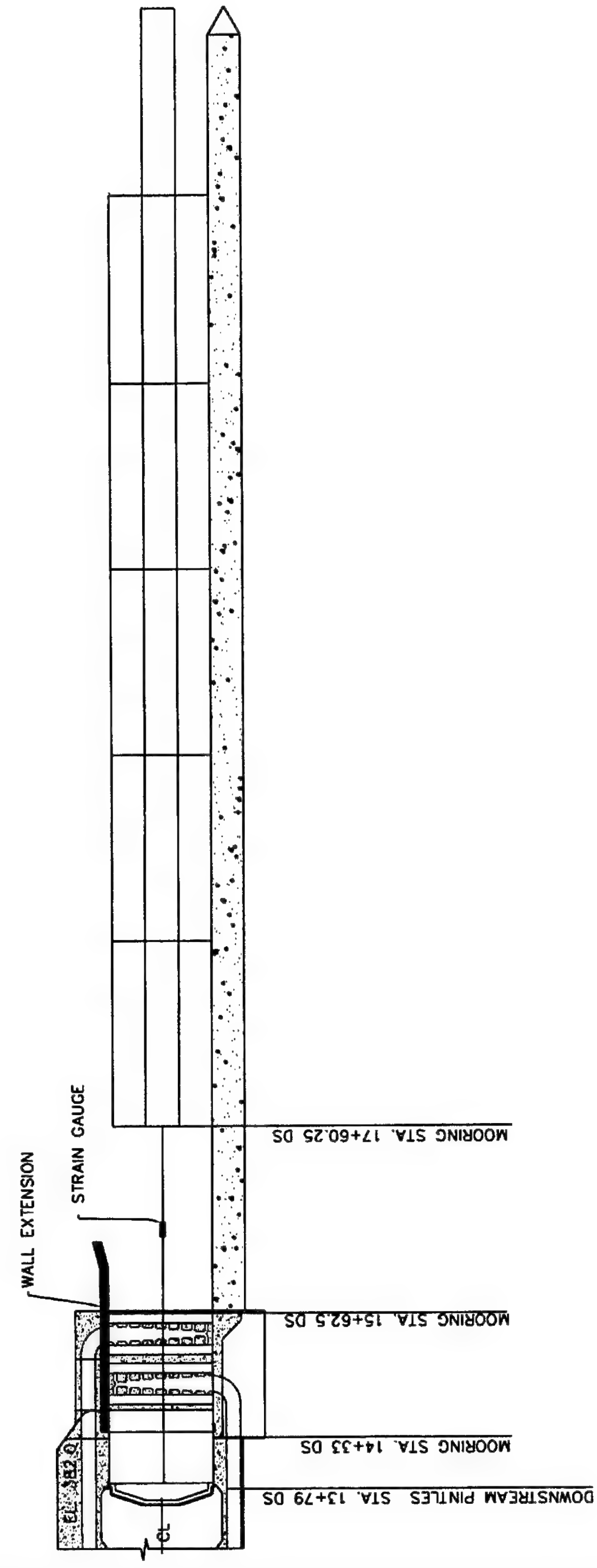
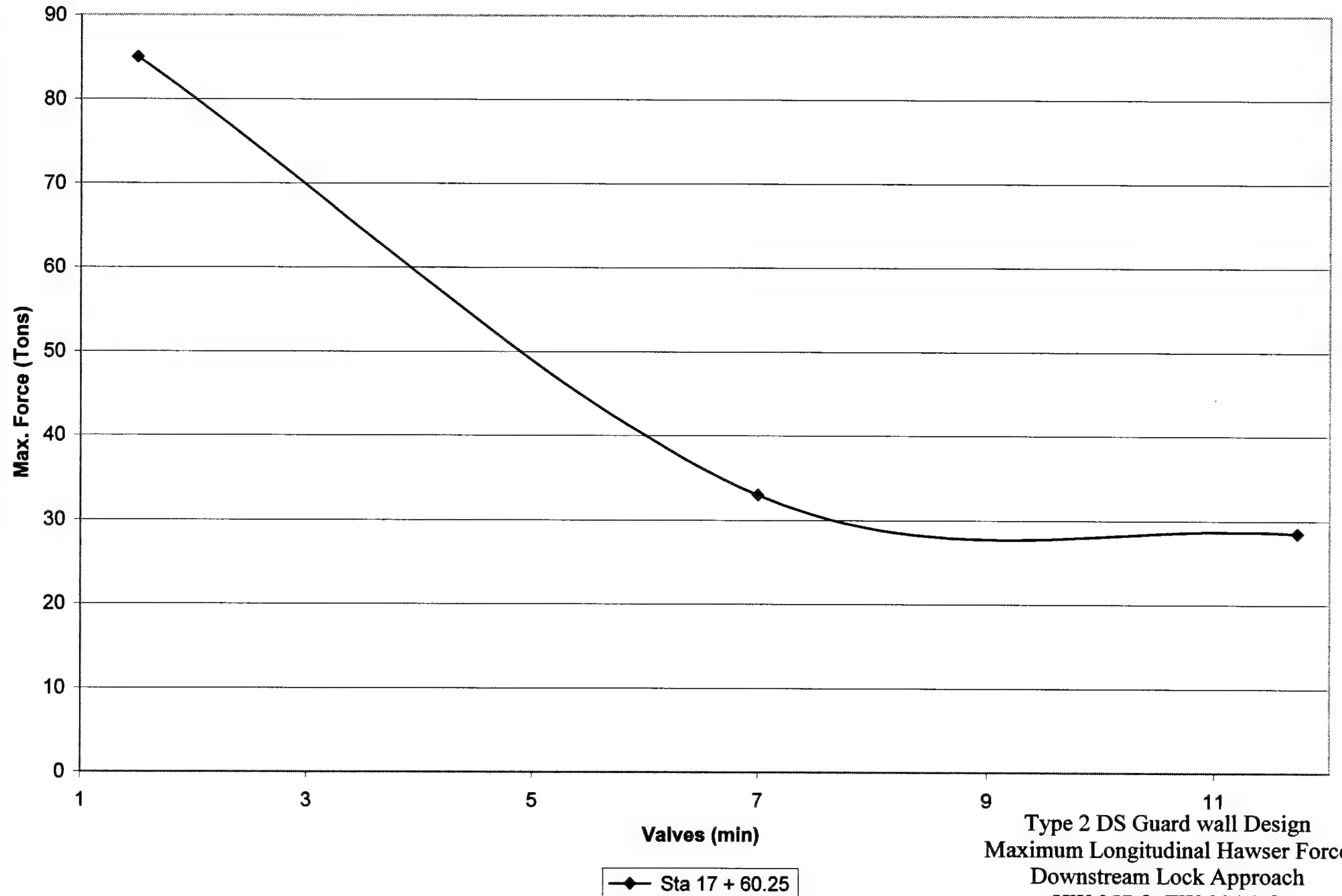

Maximum Longitudinal Hawser Force
Downstream Lock Approach
HW 359 ft, TW 314 ft
Max. Force (Tons)
0
5
10
15
20
25
DS Mooring Station
15 + 50
16 + 00
16 + 50
17 + 00
17 + 50
18 + 00
1.5 min. valve
3.0 min. valve
11.72 min. valve

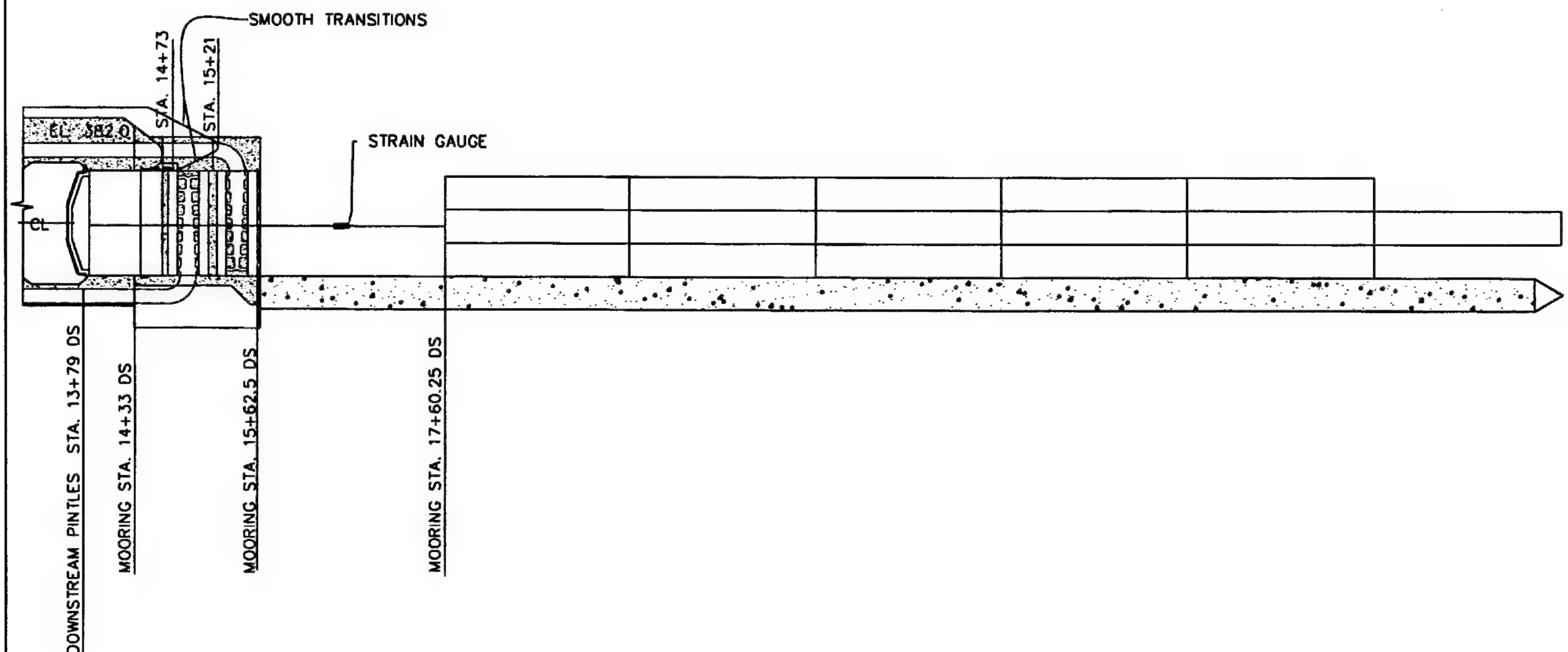
Plate 33



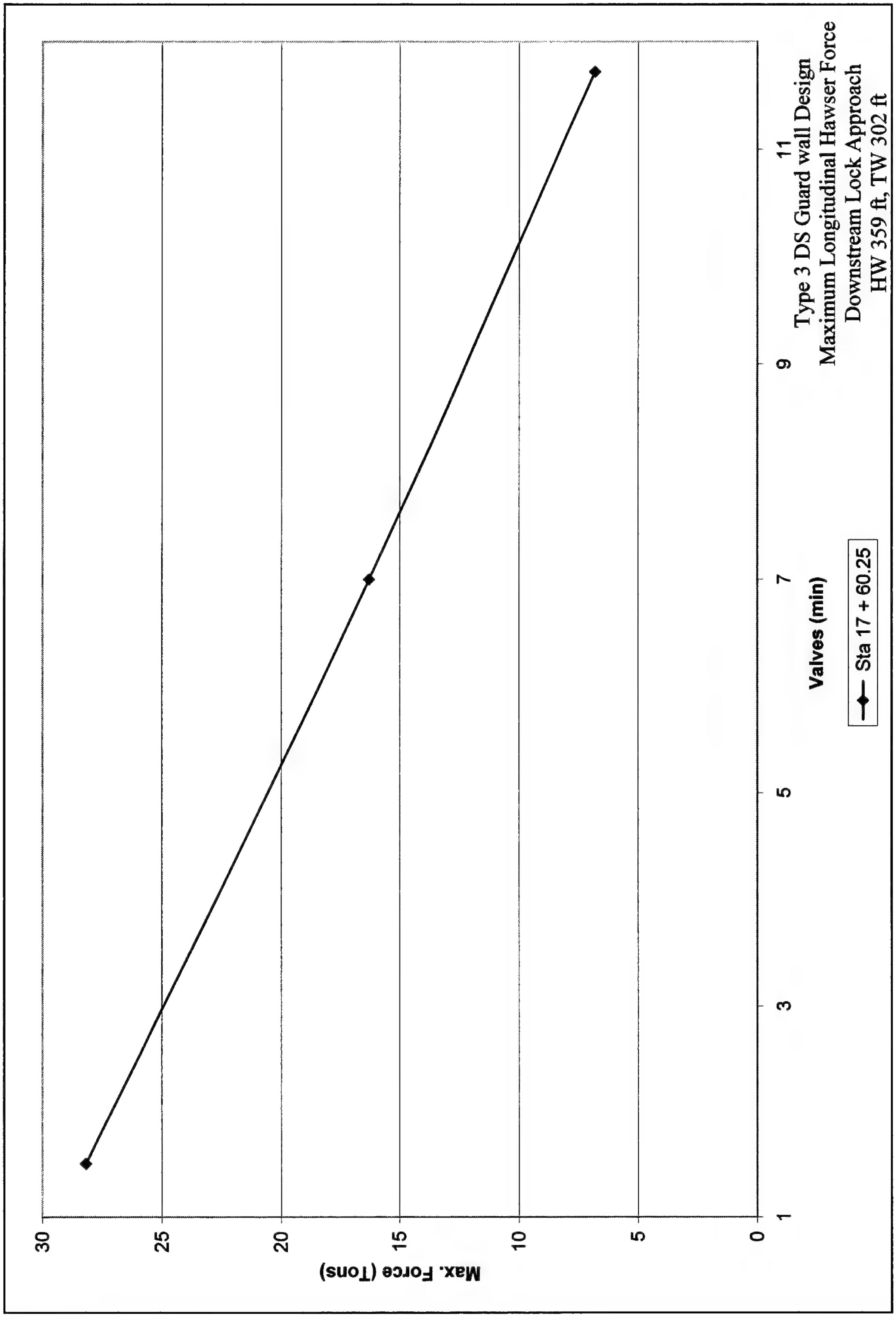
DOWNSTREAM MOORING STATIONS
TYPE 2 DOWNSTREAM GUARD WALL DESIGN

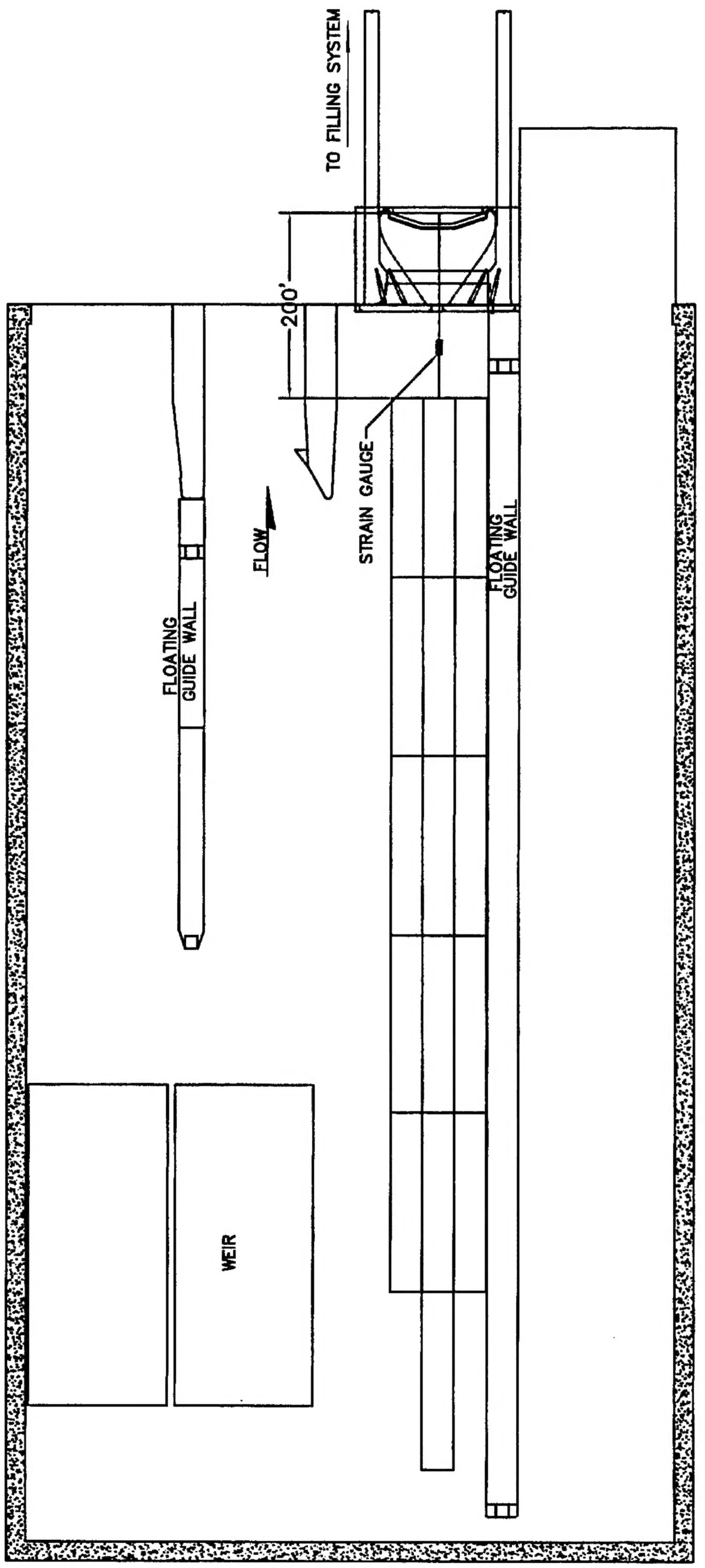


Type 2 DS Guard wall Design
Maximum Longitudinal Hawser Force
Downstream Lock Approach
HW 357 ft, TW 304.2 ft



DOWNSTREAM MOORING STATIONS
TYPE 3 DOWNSTREAM GUARD WALL DESIGN


Type 3 DS Guard wall Design
Maximum Longitudinal Hawser Force
Downstream Lock Approach
HW 359 ft, TW 302 ft
Max. Force (Tons)
0
5
10
15
20
25
30
Valves (min)
1
3
5
7
9
11
Sta 17 + 60.25



60.96-m (200-ft) FROM PINTLES
MOORING HAWSER FORCES
UPSTREAM LOCK APPROACH

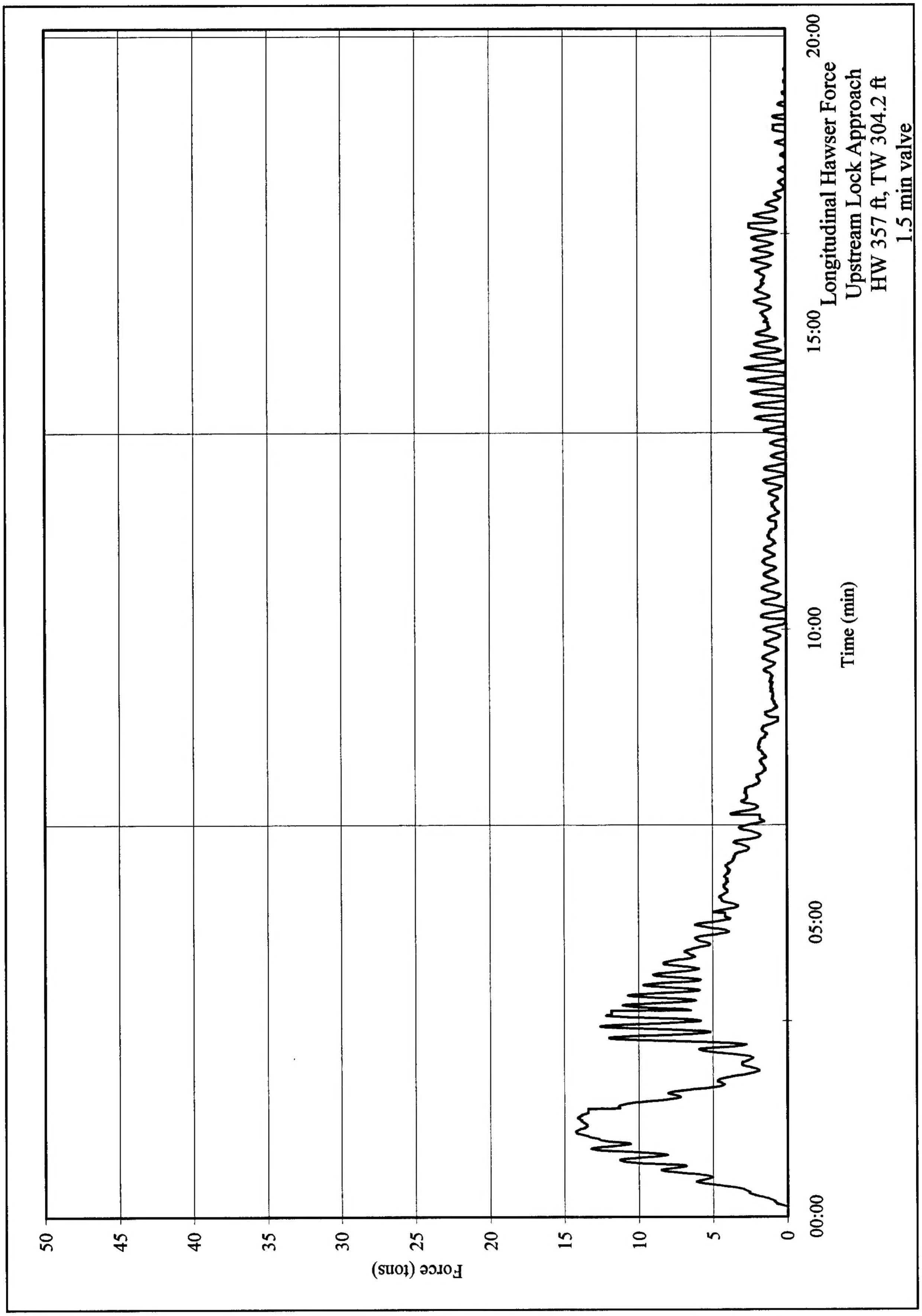
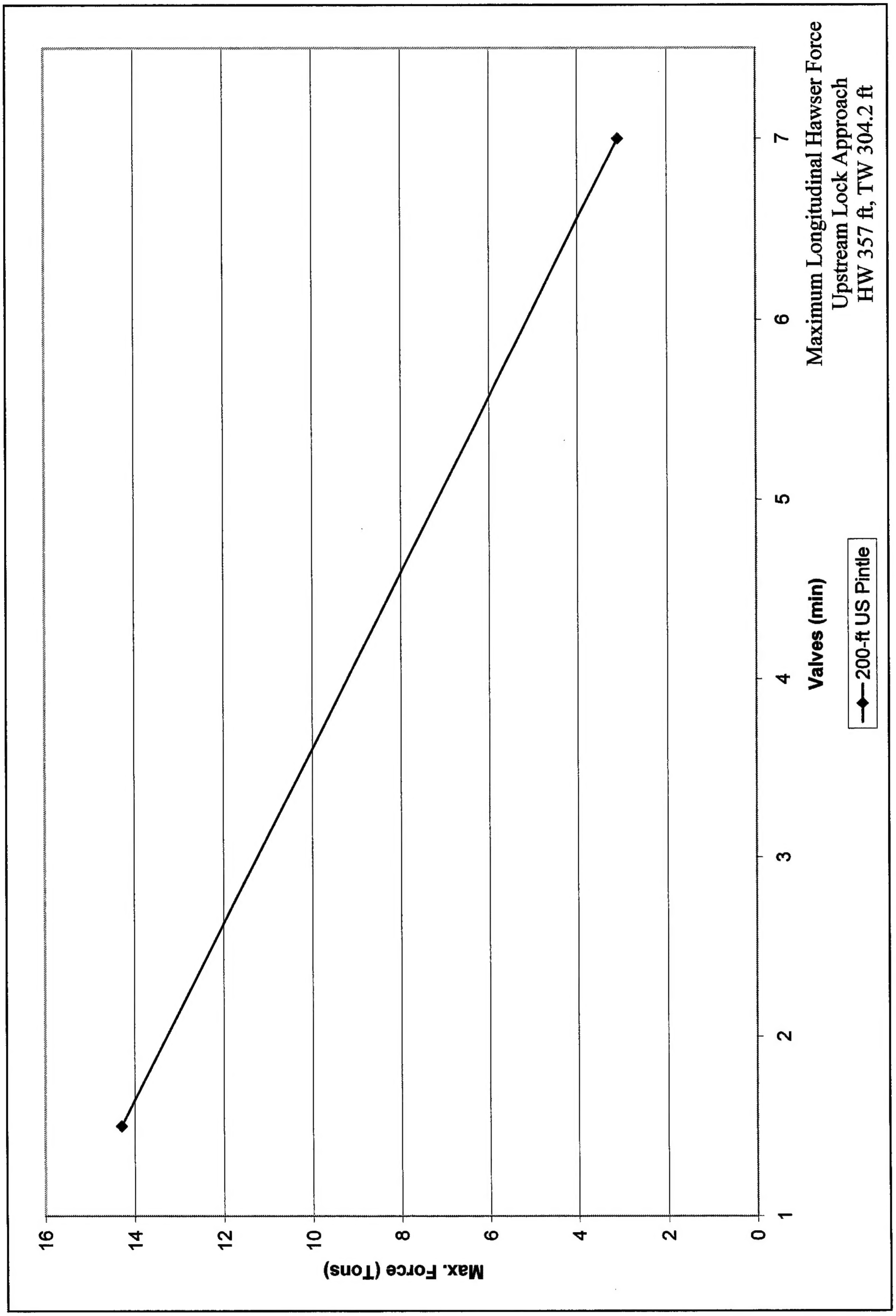

Longitudinal Hawser Force
Upstream Lock Approach
HW 357 ft, TW 304.2 ft
1.5 min valve
Force (tons)
Time (min)
0
5
10
15
20
25
30
35
40
45
50
00:00
05:00
10:00
15:00
20:00

Plate 39



Maximum Longitudinal Hawser Force
Upstream Lock Approach
HW 357 ft, TW 304.2 ft
Max. Force (Tons)
Valves (min)
200-ft US Pintle
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
7

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jose E. Sanchez

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
004HC6

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Experiments were conducted on a 1:25 scale model of the Kentucky Lock Addition Lock located on the Tennessee River in Kentucky. The model was constructed to evaluate the lock filling and emptying system performance and flow conditions in the upper and lower approaches. The system consisted of a through-the-sill intake that carries flow to a multiport arrangement, and an interlaced lateral discharge system located just downstream of the lower miter gates. The 398 ports located in the culvert walls are placed in two rows on each culvert. Modifications to the upstream lock approach were conducted to reduce the strength of vortices observed during filling operations. The flow conditions in the upper approach were improved with the type 5 approach design. With the original chamber (recommended) design and a 7.0-min valve operation for the filling cycle and a 3.0-min valve operation for the emptying cycle, the lock chamber filled in 16.3 min and emptied in 17.5 min. Experiments were performed to determine the optimum mooring location for a three-by-five barge arrangement in the lower and upper lock approach during the emptying and filling operations. The tow moored at sta 17+60.25 with a 7.0-min valve operation during the emptying cycle experienced tolerable longitudinal hawser forces. In the upstream lock approach, the barge arrangement was moored 200 ft upstream of the upper miter gates pintle, and a 1.5-min valve operation during the filling cycle yielded acceptable longitudinal hawser forces, although this valve time is not recommended when a tow is in the lock chamber.

15. SUBJECT TERMS

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